April 2004

Generating High Resolution

Climate Change Scenarios using PRECIS

NATIONAL COMMUNICATIONS SUPPORT UNIT
HANDBOOK

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GENERATING HIGH RESOLUTION CLIMATE CHANGE SCENARIOS USING PRECIS

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FOREWORD

To anticipate future climate change, we need to project how greenhouse gases will change in the future. A range of emission scenarios has been developed in the IPCC Special Report on Emissions Scenarios that reflect a number of different ways in which the world might develop ("storylines") and the consequences for population, economic growth, energy use and technology.

To estimate the effect that these emissions have on the global climate, global climate models (GCMs) are employed. GCMs describe important physical elements and processes in the atmosphere, oceans and land surface that make up the climate system. One disadvantage of GCMs is their scale, which is typically a few hundred kilometres in resolution. In order to study the impacts of climate change, we need to predict changes on much finer scales. One of the techniques for doing so is through the use of Regional Climate Models (RCMs), which have the potential to improve the representation of the climate information which is important for assessing a country's vulnerability to climate change.

However, until now, most non-Annex I Parties have not had either the resources or the capacity to use the RCM approach. PRECIS (Providing Regional Climates for Impacts Studies) is a portable RCM that can be run on a personal computer and applied to any area of the globe to generate detailed climate change scenarios. This model has been developed at the Hadley Centre and is sponsored by the UK Department for Environment, Food and Rural Affairs (DEFRA), the UK Department for International Development (DFID) and the United Nations Development Programme – Global Environment Facility (UNDP-GEF).

This Handbook describes the steps to generate high resolution climate change scenarios using PRECIS, taking into account gaps in information and understanding. It has the following objectives:

- To introduce the use of RCMs as a possible tool to generate high-resolution climate change scenarios;
- To describe how to use PRECIS to generate these scenarios;
- To outline the limitations of PRECIS; and
- To present ways to use PRECIS output for impact assessments.

These issues are addressed in more detail in a Workshop the Hadley Centre runs for prospective users of PRECIS.

Although substantial resources and data are required, PRECIS is already being used to generate scenarios for India, China and southern Africa, using bilateral funding.

This Handbook is aimed at non-Annex I Parties that are engaged in the process of preparing vulnerability and adaptation (V&A) assessments for their National Communications under the United Nations Framework Convention on Climate Change (UNFCCC). The use of this Handbook can facilitate the construction of regional climate scenarios. More importantly, the Handbook stresses that an RCM does not replace GCMs, but is a tool to be used together with the GCMs. The Hadley Centre also acknowledges that the quality of regional predictions is limited by the uncertainties in the global models that drive the RCMs. The Handbook explains not only the uses and advantages of PRECIS, but also its limitations.

The Support Programme does not prescribe or endorse any single approach in V&A assessments. Rather, PRECIS is presented as one tool that is available for use. Further details on the PRECIS software are provided in a companion Technical Manual (Wilson *et al.*, 2004).

Frank Pinto
Executive Director
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The National Communications Support Unit does not endorse the use of any single model or method for national-scale assessments of climate change.
It encourages the use of a range of models and methods appropriate to national circumstances.

1 INTRODUCTION

1.1 Background

"An increasing body of observations gives a collective picture of a warming world and other changes in the climate system." (IPCC WGI TAR, 2001). These other changes include the decrease in snow cover and ice extent, rise in sea level, regional variations of precipitation patterns, and changes in extremes of weather and climate. These recent regional changes, particularly temperature increases, have already affected many physical and biological systems. The rising socio-economic costs coming from climate-related damage and regional variations in climate suggest increasing vulnerability to climate change. But what is causing all these changes? "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities mainly brought about through changes in the atmospheric composition due to the increase in emissions of greenhouse gases and aerosols" (IPCC WGI TAR, 2001). What are the projections for the future? Human influence will continue to change atmospheric composition throughout the 21st century and hence global average temperature and sea level are projected to rise.

Humans' actions are starting to interfere with the global climate. Recognising that the problem is global, and in response to a series of international conferences and the work of the Intergovernmental Panel on Climate Change, the United Nations, in 1990, set up a Committee to draft a Framework Convention on Climate Change. The Convention was adopted in 1992 and received 155 signatures at the June 1992 United Nations Conference on Environment and Development (known as the Rio Earth Summit). The objective of the Convention is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." (Article 2, UNFCCC: http://unfccc.int).

Under Article 4.1 and 4.8 of the UN Framework Convention on Climate Change (UNFCCC), all Parties have the requirement to assess their national vulnerability to climate change and to submit National Communications. To this effect, the National Communications Support Unit (NCSU) is developing an integrated package of methods to assist developing countries to develop adaptation measures to climate change. Assessments of vulnerability are informed by estimates of the impacts of climate change, which in turn are often based on scenarios of future climate. These scenarios are generally derived from projections of climate change undertaken by Global Climate Models (GCMs). These GCM projections may be adequate up to a few hundred kilometres or so, however they do not capture the local detail often needed for impact assessments at a national and regional level. One widely applicable method for adding this detail to global projections is to use a regional climate model (RCM). Other techniques include the use of higher resolution atmospheric GCMs and statistical techniques linking climate information at GCM resolution with that at higher resolution or at point locations. These approaches, with their strengths and weaknesses, are discussed in Section 4.

The provision of a flexible RCM is thus part of an integrated package of methods, which would also include a range of GCM projections for assisting countries to generate climate change scenarios and hence to inform adaptation decisions. The Hadley Centre has developed such a flexible RCM to provide non-Annex I Parties with a practical tool to make their own projections of national patterns of climate change and hence estimate the possible impacts and assess their vulnerability. **It must be stressed that the RCM does not replace GCMs, but it is a powerful tool to be used together with the GCMs in order to add fine-scale detail to their broad-scale projections.**

This new regional modelling system, PRECIS (Providing Regional Climates for Impacts Studies, pronounced pray-sea, i.e. as in French), has been developed at the Hadley Centre and is sponsored by the UK Department for Environment, Food and Rural Affairs (DEFRA), the UK Department for International Development (DFID) and the United Nations Development Programme (UNDP). PRECIS runs on a personal computer (PC) and comprises:

- An RCM that can be applied easily to any area of the globe to generate detailed climate change projections,
- A simple user interface to allow the user to set up and run the RCM, and
- A visualisation and data-processing package to allow display and manipulation of RCM output.

PRECIS is made available at workshops run regularly by Hadley Centre staff (generally in the region where it is to be used) which are provided to address the many issues involved in its application. Support and follow-up are provided via the PRECIS website and an email-based help line (for more information, please see the inside back cover of this handbook). A sample display of PRECIS configured for a region over New Zealand is provided in Figure 1.

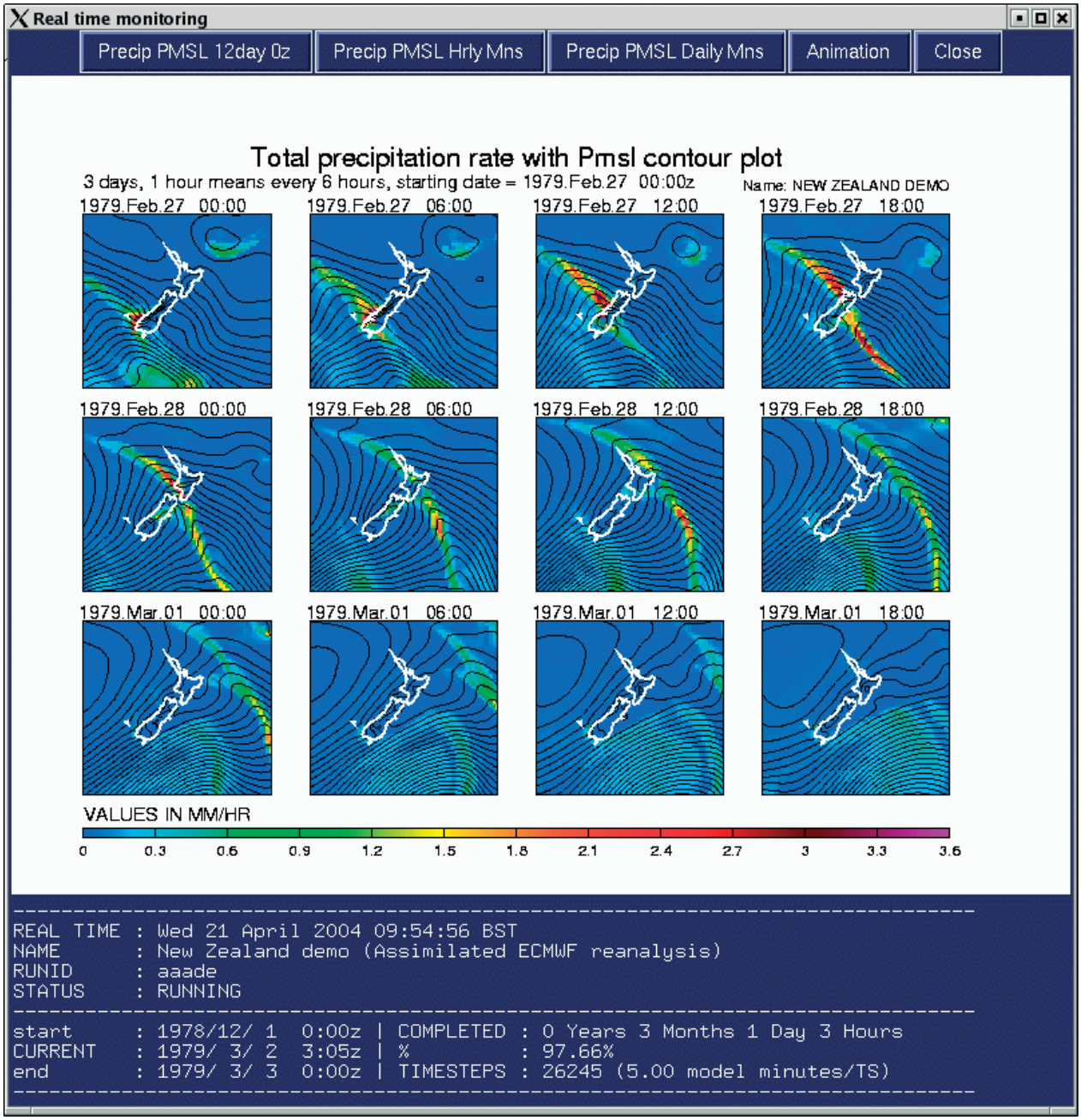


Figure 1: *Example output monitoring the PRECIS RCM running over New Zealand, showing (from top left, clockwise) maps of rainfall (shaded) and mean sea level pressure isobars (contoured) at 6 hourly intervals for three successive days of a model integration.*

PRECIS is freely available for use by developing country scientists, with priority given to those involved in vulnerability and adaptation studies conducted by their governments that are to be reported in National Communications to the UNFCCC. Section 6.2 summarises the resources required when using PRECIS and its applicability. It is important that adaptation decisions are based on a range of climate scenarios accounting for the many uncertainties associated with projecting future climate (Section 3). These are most conveniently derived by groups of neighbouring countries working together over a certain region. National climate change scenarios can then be created locally for use in impact and vulnerability studies using local knowledge and expertise. Carrying out the work at regional level will lead to much more effective dissemination of scientific expertise and awareness of climate change impacts than could be achieved by simply handing out results generated from models run in developed countries. It will also tap into valuable local knowledge, for example in checking the validity of models against observations from the region of interest. By encouraging and facilitating the use of RCMs, it is hoped that PRECIS will contribute to

technology transfer and capacity building, important aspects of Article 4 of the UNFCCC.

Whilst projections from RCMs are undoubtedly very powerful aids to planning and adaptation, uncritical use of their output could lead to misinterpretation, and it is important that prospective users understand the limitations of all methods for generating climate scenarios, as well as their advantages. To address this, the Hadley Centre has prepared a comprehensive workshop for prospective users of PRECIS. The workshop provides background on the science of climate change, global and regional modelling of the climate system and explains about other methods for obtaining high resolution climate change information, so that users are aware of these. The workshop also provides in-depth training on the installation and use of PRECIS, including hands-on work and opportunities for users to discuss and plan collaborative work. Finally, examples are given of how climate scenarios may be produced and used.

To allow local groups of countries to proceed with the use of PRECIS largely independently, a companion technical manual (Wilson *et al.*, 2004) has also been prepared, and PC and internet-based help information is available. The latter includes information on what PRECIS is being used for, future plans, any updates to PRECIS, relevant datasets which users may find useful (and are small enough to be downloaded), a list of resources such as relevant papers and reports and a bulletin board where users may share experience and ask or answer specific queries. Advice is also available directly from the Hadley Centre from the contact email address printed in the back of this handbook and the technical manual. Finally, Hadley Centre staff are keen to collaborate on research and scientific publications involving PRECIS and to attend, and possibly help organise, workshops where collaborators are presenting and discussing results from PRECIS.

1.2 Objective and Structure of the Handbook

The objective of this Handbook is to describe the steps required to generate high-resolution climate change scenarios using PRECIS, taking into account remaining gaps in information and understanding. This general objective has four main parts:

- To introduce the use of Regional Climate Models as a viable tool to generate high-resolution climate change scenarios
- To describe how to use PRECIS to generate these scenarios
- To outline the limitations of PRECIS
- To present ways to use PRECIS output for impact assessments.

The Handbook is structured as follows. The next section describes the general steps required to construct future climate scenarios starting from a range of IPCC emissions projections and going through to their implications for possible changes in future climate. Section 3 discusses the uncertainty in these scenarios, based on the uncertainties associated with each of these steps. Section 4 then looks at the various methods for obtaining climate change scenarios and in particular at a resolution appropriate for assessing their possible socio-economic impacts. Section 5 describes in more detail the method used to generate high resolution climate change scenarios, i.e. the RCM. Section 6 then describes the PRECIS regional climate modelling system and Section 7 describes how to use it for generating regional climate scenarios. Both Sections 5 and 7 include examples of the use of PRECIS. Section 8 provides details of planned further developments relevant to PRECIS and to high resolution climate change scenario production.

Note that this Handbook is not designed to be a comprehensive guide to all aspects of climate scenario generation, nor to their advantages, disadvantages and practicalities in different situations. Although brief mention is given to a range of techniques, to encourage a wide variety of approaches, it focuses squarely on the use of RCMs, and PRECIS in particular. Prospective users of PRECIS are referred to Chapter 10 and Chapter 13 of the Working Group 1 contribution to the IPCC Third Assessment Report (IPCC TAR WG1 report, respectively, Giorgi *et al.*, 2001 and Mearns *et al.*, 2001), Chapter 3 of IPCC TAR WG2 report (Carter *et al.*, 2001) and also to guidance (http://ipccddc.cru.uea.ac.uk/guidelines/guidelines_home.html) given by the IPCC Task Group on Climate Impacts Assessments (TGCIA) (Mearns *et al.*, 2003).

2 CONSTRUCTING CLIMATE SCENARIOS FOR IMPACT STUDIES

In order for individual countries to assess climate impacts, they require scenarios of future climate change. A climate scenario is a plausible, self-consistent outcome of the future climate that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate projections, using for example simulations of future climate using climate models. Figure 2 provides an overview of the main sequences of steps with which the various types of climate scenarios are constructed.

Although studies of the *sensitivity* of socio-economic activities (e.g. agriculture) use simple "whole number" changes in climate (e.g. the impact of a uniform increase in temperature of 2K), the basis for all climate scenarios for use in *adaptation* assessments are projections of climate change from GCMs. (Clearly, this is not the same as saying that all adaptation studies require climate scenarios.) These climate projections depend upon the future changes in emissions or concentrations of greenhouse gases and other pollutants (e.g. sulphur dioxide), which in turn are based on assumptions concerning, e.g., future socio-economic and technological developments, and are therefore subject to substantial uncertainty. For this reason, we need to generate a number of climate scenarios which cover the plausible range of future emissions. With this requirement in mind, the recent IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al.*, 2000) has provided such scenarios, and these are used as the basis of climate scenarios in this Handbook. Users should recognise the inherent uncertainty of scenarios when communicating results to policy makers.

The main stages required to provide climate change scenarios for assessing the impacts of climate change are presented in Figure 3. Here regional detail is shown to be obtained from RCMs as this is the approach taken by PRECIS.

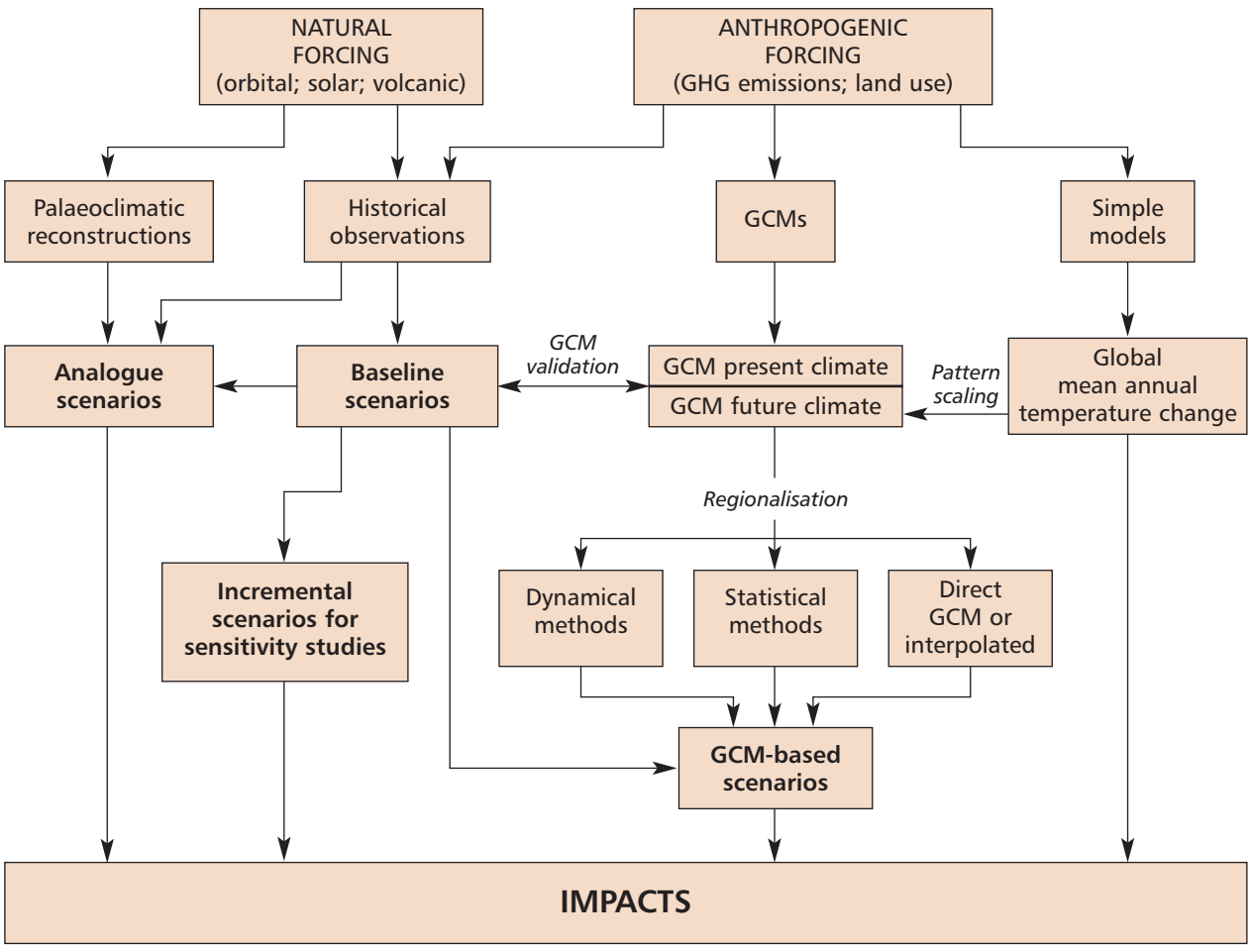


Figure 2: *Procedures for constructing climate scenarios for use in impact assessments. From Mearns et al. (2001).*

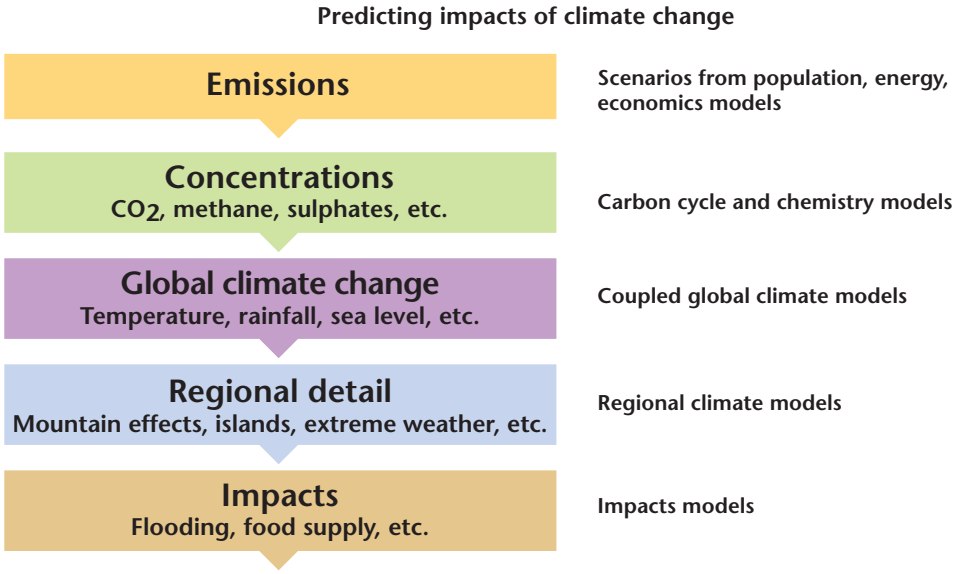


Figure 3: *The main stages required to provide climate change scenarios for assessing the impacts of climate change.*

1. Emission scenarios

We will never know exactly how anthropogenic emissions will change in the future. However, the IPCC SRES has developed new emission scenarios, the so-called "SRES scenarios". Emission scenarios are plausible representations of future emissions of substances that are radiatively active (i.e greenhouse gases) or which can affect constituents which are radiatively active (e.g. sulphur dioxide which forms sulphate aerosols). These are based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development and technological change) and their key relationships. The SRES scenario set comprises four scenario families: A1, A2, B1 and B2. The scenarios within each family follow the same picture of world development ("storyline" – see Box 1). The A1 family includes three groups reflecting a consistent variation of the storyline (A1T, A1FI and A1B). Hence, the SRES emissions scenarios consist of six distinct scenario groups, all of which are plausible and together capture the range of uncertainties associated with driving forces.

2. Concentration estimations

Carbon cycle and atmospheric chemistry models are used to calculate concentrations and burdens of different gases and substances which follow from the above emission scenarios. In the case of carbon dioxide, we follow the concentration profiles calculated using the Bern model (Joos *et al.*, 1996), as these were used as the basis of all the GCM projections in Chapter 9 of the IPCC TAR WGI report (Cubasch *et al.*, 2001). In the case of other greenhouse gases (including ozone) we use 2d- and 3d-models to estimate concentrations. The generation of sulphate aerosol in the model from sulphur dioxide (SO_2) emissions is discussed in Annex I section 2.

3. Global Climate Models

Concentration scenarios described above are used as input into climate models to compute global climate projections. A GCM is a mathematical representation of the climate system based on the physical properties of its components, their interactions and feedback processes. Most models account for the most important physical processes; in some cases chemical and biological processes are also represented. Many GCMs simulate the broad features of current climate well and most can reproduce the observed large-scale changes in climate over the recent past, so can be used with some confidence to give projections of the response of climate to current and future human activities. Climate models have developed over the past few decades as computing power has increased. During this time, models of the main components, atmosphere, ocean, land and sea ice, have gradually been integrated and coupled together and representations of the carbon cycle and atmospheric chemistry are now being introduced. Currently the resolution of the atmospheric part of a typical GCM is about 250 km in the horizontal with 20 levels in the vertical. The resolution of a typical ocean model is 125 km to 250 km, with, again, 20 levels from the sea surface to the ocean floor. Hence GCMs make projections at a relatively coarse resolution and cannot represent the fine-scale detail that characterises the climate in many regions of the world, especially in regions with complex orography or heterogeneous

land surface cover or coastlines. As a result, "GCMs cannot access the spatial scales that are required for climate impact and adaptation studies" (WMO, 2002) though a lack of resolution is not necessarily a major factor to consider when constructing comprehensive climate scenarios for impacts studies. Historically, GCMs have been the primary source of information for constructing climate scenarios and will always provide the basis of comprehensive assessments of climate change at all scales from local to global (see e.g. Chapter 13 of the IPCC TAR WG1 report (Mearns *et al.*, 2001) and Carter *et al.*, 1994).

4. Regional Climate Models

To conduct thorough assessments, impact researchers need regional detail of how future climate might change, which in general should include information on changes in variability (e.g. Arnell *et al.*, 2003) and extreme events. An RCM is a tool to add small-scale detailed information of future climate change to the large-scale projections of a GCM. RCMs are full climate models and as such are physically based and represent most or all of the processes, interactions and feedbacks between the climate system components that are represented in GCMs. They take coarse resolution information from a GCM and then develop temporally and spatially fine-scale information consistent with this using their higher resolution representation of the climate system. In general they do not model oceans, as this would substantially increase the computing cost yet, in many cases, would make little difference to the projections over land that most impacts assessments require. The typical resolution of an RCM is about 50 km in the horizontal. It covers an area (domain) typically 5000 km x 5000 km, located over a particular region of interest.

Box 1: SRES Scenario storylines

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered plausible but we have no way of knowing their relative probabilities; for example there is no reason to assume they are all equally probable.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol. In particular, none involves a stabilization of concentrations of greenhouse gases.

3 UNCERTAINTIES

There are uncertainties in each of the main stages required to provide climate change scenarios for assessing the impacts of climate change. These uncertainties must be taken into account when assessing the impacts, vulnerability and adaptation options. However, not all the aspects of these uncertainties can be quantified yet (see Chapter 13 of the IPCC TAR WG1 report (Mearns *et al.*, 2001)).

The sources of these uncertainties and how they can be accounted for are summarised in Table 1. Those represented in the current experimental set-up for PRECIS are also documented in the table.

1. Uncertainties in future emissions
There are inherent uncertainties in the key assumptions about and relationships between future population, socio-economic development and technical changes that are the bases of the IPCC SRES Scenarios. The uncertain nature of these emissions paths has been well documented (Morita *et al.*, 2001). The uncertainty in emissions can be allowed for by making climate projections for a range of these SRES emissions scenarios. We have driven the Hadley Centre GCM with SRES A1FI, A2, B2 and B1 emissions, which cover most of the range of uncertainty, and these global projections can in turn be regionalised using the PRECIS system. Emissions uncertainty is currently regarded as one of the two clearly identified major causes of uncertainty in projected future climate.

2. Uncertainties in future concentrations
The imperfect understanding of some of the processes and physics in the carbon cycle and chemical reactions in the atmosphere generates uncertainties in the conversion of emissions to concentration. However, following the IPCC TAR, we have not reflected uncertainties in the emission-to-concentration relationships, using (in the case of carbon dioxide (CO_2)) the concentration estimated by the Bern model. A potentially even larger uncertainty arises in the feedbacks between climate and the carbon cycle and atmospheric chemistry. To reflect this uncertainty in the climate scenarios, the use of atmosphere-ocean general circulation models (AOGCMs) that explicitly simulate the carbon cycle and chemistry of all the substances is needed. One experiment using a climate model that allows carbon cycle feedback showed a substantially faster warming than when this feedback is neglected (Cox *et al.*, 2002). In another example, incorporating atmospheric chemistry feedbacks substantially slowed increases in methane and tropospheric ozone (Johnson *et al.*, 2001). However, because this work is in its infancy, we do not yet have sufficient confidence in the results to use them to drive PRECIS.

3. Uncertainty in the response of climate.
There is much we do not understand about the workings of the climate system, and hence uncertainties arise because of our incorrect or incomplete description of key processes and feedbacks

Source of Uncertainty	Represented in PRECIS?	Ways to address it
Future emissions	Yes	Run climate model for a range of emission scenarios
Emissions to concentrations	No	Use a number of carbon cycle and atmospheric chemistry models
Incomplete understanding / imperfect representation of processes in climate models ("science uncertainty")	Under development see Section 8	Use projections from a range of GCMs
Natural variability	Yes	Use an ensemble of GCM projections with different initial conditions
Adding spatial and temporal detail	No	Use other RCMs or statistical downscaling in parallel with PRECIS

Table 1: *Ways to address some of the uncertainties encountered when constructing climate scenarios.*

in the model. This is clearly illustrated by the fact that current global climate models, which contain different representations of the climate system, project different patterns and magnitudes of climate change for the same period in the future when using the same concentration scenarios (see e.g. Chapter 9 of the IPCC TAR WG1 report (Cubasch *et al.*, 2001) and Figure 4). It is for this reason that we also **STRONGLY** recommend the use of a number of different GCMs as input to climate impacts studies, despite their poor resolution, to reflect (at least in part) this "science uncertainty". The uncertainty attributed to the global climate response is the other major uncertainty currently identified along with the uncertainty of future emissions discussed above.

4. Uncertainty due to natural variability

The climate varies on timescales of years and decades due to natural interactions between atmosphere, ocean and land, and this natural variability is expected continue into the future. For any given period in the future (e.g. 2041-2070) natural variability could act to either add to or subtract from changes (for example in local rainfall) due to human activity. This uncertainty cannot yet be removed, but it can be quantified. This is done by running ensembles of future climate projections; each member of the ensemble uses the same model and the same emission or concentration scenario, but each run is initiated from a different starting point in the "control" climate. The results of this ensemble for a particular 10- or 30-year period will give a range of possible futures which are likely to span the actual evolution of the climate system, assuming the representation in the climate model to be correct.

5. Uncertainty in regional climate change

Uncertainty in regional climate change is discussed comprehensively in Chapters 10 and 13 of IPCC WG1 TAR (Giorgi *et al.*, 2001 and Mearns *et al.*, 2001). The first point to be made is that all regionalisation techniques carry with them any errors in the driving GCM fields; although this is not an uncertainty in regionalisation, it must be borne in mind. Different regionalisation techniques (described in the next section) can give different local projections, even when based on the same GCM projection. Even with the same technique, different RCMs will give different regional projections, even when based on the same GCM output. Comparisons of these have only recently begun (e.g. in the EU PRUDENCE project- http://www.dmi.dk/f+u/klima/prudence/index.html and Pan *et al.*, 2001). Again, see IPCC TAR WG1 Chapter 13 (Mearns *et al.*, 2001) for a more complete coverage of uncertainties.

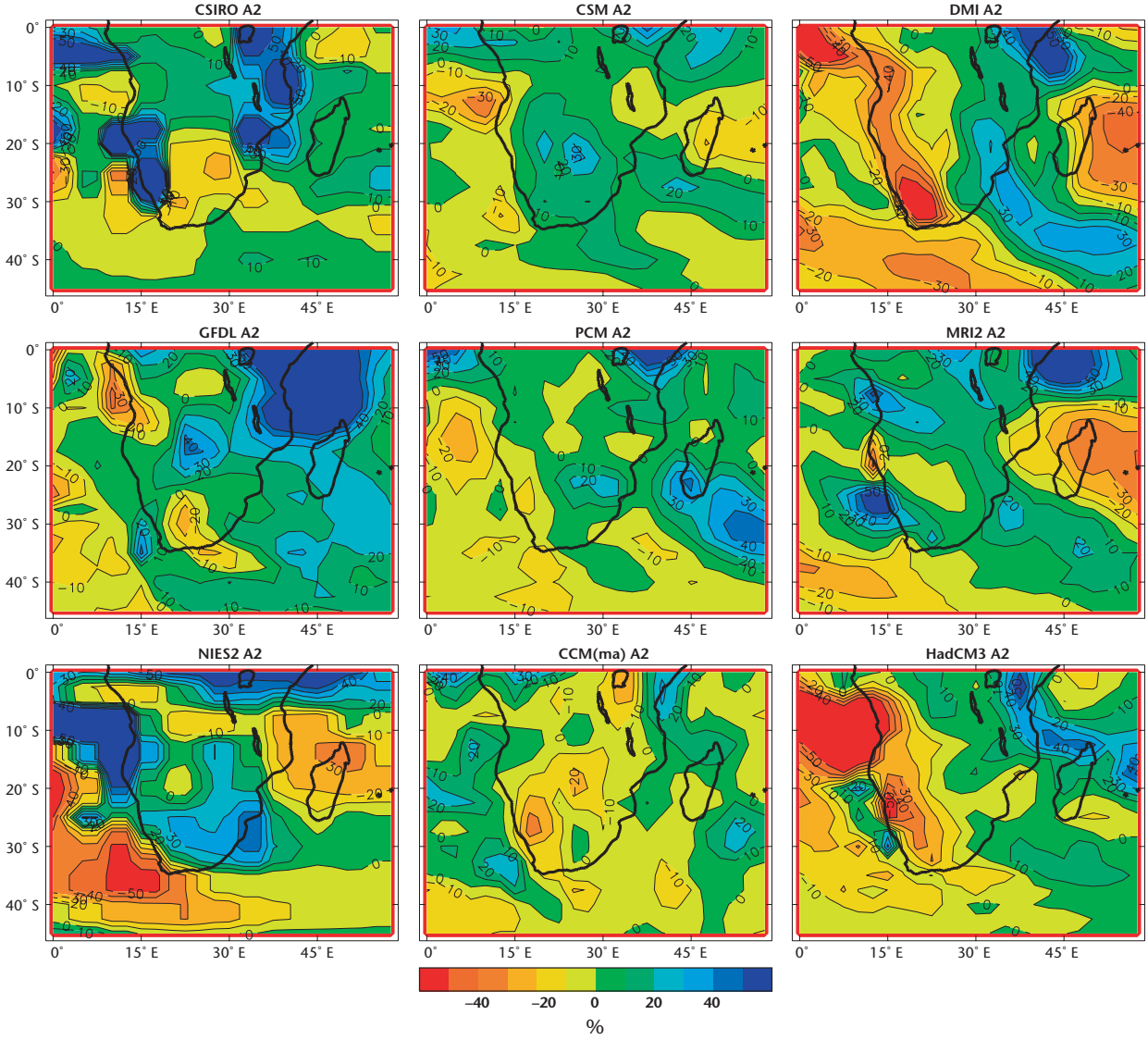


Figure 4: *Thirty-year mean change in summer (DJF) precipitation (%) for the 2080s relative to the present day under the A2 emissions scenario for nine different fully coupled ocean-atmosphere GCMs. [CSIRO: Commonwealth Scientific and Industrial Research Organisation's Mk2 model (Australia); CSM: Climate System Model, National Centre for Atmospheric Research (USA); DMI: Max-Plank Institute for Meteorology (Germany) and Danish Meteorological Institute's ECHAM4- OPYC model; GFDL: Geophysical Fluid Dynamical Laboratory's R30-C model; PCM: Department of Energy (USA) and the National Centre for Atmospheric Research's Parallel Climate Model; MRI2: Meteorological Research Institute's (Japan) GCM (V2); NIES2: Centre for Climate Study Research (Japan) and National Institute for Environmental Studies' (Japan) GCM (V2); CCC(ma): Canadian Center for Climate (Modelling and Analysis) CGCM2 model; HadCM3: Hadley Centre GCM]*

4 TECHNIQUES FOR OBTAINING REGIONAL CLIMATE CHANGE PROJECTIONS

GCMs' projections of climate change are the starting point for most climate scenarios though they lack the regional detail that impact studies generally need (Table 2). In this connection, different techniques have been developed which allow fine scale information to be derived from the GCM output (See IPCC WG1 TAR Chapter 10, Giorgi *et al.*, 2001). The approaches can be divided into three general categories: statistically based, dynamically based and a hybrid (i.e. statistical-dynamical). Note that the process of interpolating change between GCM grid points adds no high-resolution information and so the interpolated fields can be misleading (possibly with the exception of temperature), especially in regions where local forcings (e.g. complex physiography) or higher resolution physical processes (e.g. the formation of tropical cyclones) are important.

Statistical:
This approach is based on the construction of relationships between the large-scale and local variables calibrated from historical data. These statistical relationships are then applied to the large-scale climate variables from an AOGCM simulation or projection to estimate corresponding local and regional characteristics. A range of methods has been developed, and is described in IPCC TAR WG1 Chapter 10 (Giorgi *et al.*, 2001). The utility of this technique depends upon two assumptions:

a) high quality large-scale and local data being available for a sufficiently long period to establish robust relationships in the current climate
b) relationships which are derived from recent climate being relevant in a future climate.

This last assumption appears to hold well for temperature. However, for precipitation, circulation is the dominant factor in the relationships in recent climate, whereas in a future climate, change in humidity will be an important factor.

The main advantages of this approach are that it is computationally very inexpensive and it can provide information at point locations. The main disadvantages are that the statistical relationships may not hold in a future climate and that long time series of relevant data are required to form the relationships. (See Table 2.)

Dynamical:
This approach uses comprehensive physical models of the climate system. This allows direct modelling of the dynamics of the physical systems that characterise the climate of a region. Two main modelling techniques have been employed:

High resolution and variable resolution atmospheric GCMs (AGCMs): An AGCM is run for a specific period of interest (e.g. a future decade) with boundary conditions of surface temperature and ice concentrations specified at sea points. Respectively, they operate at resolutions of around 100 km globally (e.g. May and Roeckner, 2001) or 50 km locally (e.g. Deque *et al.*, 1998). Boundary conditions for climate projections are derived from coupled GCM experiments.

RCMs: These are applied to certain periods of interest, driven by sea-surface temperatures (SSTs) and sea-ice and also boundary conditions along the lateral (atmospheric) boundaries (for example, winds and temperatures). The minimum resolution generally used for an RCM is around 50 km, and RCMs are now beginning to be used for climate simulations at twice or three times this resolution. Boundary conditions can be derived from either coupled or atmospheric GCMs.

The main advantages of these techniques are that they provide high resolution information on a large physically consistent set of climate variables and better representation of extreme events. The AGCMs provide global consistency, allowing for large-scale feedbacks, and the RCMs provide consistency with the large scales of their driving GCMs. The main disadvantages of the AGCMs are that they are computationally expensive and that if they use the same formulation as a lower-resolution version, errors in simulation of current climate can be worse. The main disadvantages of RCMs are that they inherit the large-scale errors of their driving model and require large amounts of boundary data previously archived from relevant GCM experiments. (See Table 2.)

Statistical/Dynamical:
This approach combines the ideas of obtaining statistics of large-scale climate variables and then obtaining the corresponding high-resolution climate information not from observations but from RCMs. Two variants of this approach have been developed. The first variant uses an RCM driven by observed boundary conditions from certain well-defined large-scale weather situations. A GCM simulation is then decomposed into a sequence of these weather situations and the high-resolution surface climate is inferred from the corresponding RCM simulations (Fuentes and Heimann, 2000). The second variant uses a similar approach but the first step is applied using GCM boundary conditions so giving relationships between the GCM and RCM simulations in the defined GCM large-scale weather situations (Busch and Heimann, 2002). These relationships can then be applied to periods of a GCM simulation for which no RCM has been run to infer high-resolution climate information for these periods.

The advantages and disadvantages of the first variant are similar to those of the pure statistical approach, although the requirement for long time-series of observed high-resolution data is absent. In the case of the second variant, a lack of constancy of the statistical relationships between GCM and RCM data can be verified and possibly allowed for. If the relationships are not constant, but depend on simple large-scale climate parameters (e.g. global mean temperature, regional specific humidity), then they could be generalised to include these dependencies.

Table 2: *The role of some types of climate scenarios and an evaluation of their advantages and disadvantages according to the five criteria listed below the Table. Note that in some applications a combination of methods may be used. From Mearns et al.(2003).*

Scenario type or tool	Description/Use	Advantages*	Disadvantages*
Climate model based: Direct AOGCM outputs	• Starting point for most climate scenarios • Large-scale response to anthropogenic forcing	• Information derived from the most comprehensive, physically-based models (1,2) • Long integrations (1) • Data readily available (5) • Many variables (potentially) available (3)	• Spatial information is poorly resolved (3) • Daily characteristics may be unrealistic except for very large regions (3) • Computationally expensive to derive multiple scenarios (4,5) • Large control run biases may be a concern for use in certain regions (2)
High resolution/stretched grid (AGCM)	• Providing high resolution information at global/continental scales	• Provides highly resolved information (3) • Information is derived from physically-based models (2) • Many variables available (3) • Globally consistent and allows for feedbacks (1,2)	• Computationally expensive to derive multiple scenarios (4,5) • Problems in maintaining viable parameterizations across scales (1,2) • High resolution is dependent on SSTs and sea ice margins from driving model (AOGCM) (2)
Regional models	• Providing high spatial/temporal resolution information	• Provides very highly resolved information (spatial and temporal) (3) • Information is derived from physically-based models (2) • Many variables available (3) • Better representation of some weather extremes than in GCMs (2,4)	• Computationally expensive, and thus few multiple scenarios (4,5) • Lack of two-way nesting may raise concern regarding completeness (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Statistical downscaling	• Providing point/high spatial resolution information	• Can generate information on high resolution grids, or non-uniform regions (3) • Potential for some techniques to address a diverse range of variables (3) • Variables are (probably) internally consistent (2) • Computationally (relatively) inexpensive (5) • Suitable for locations with limited computational resources (5) • Rapid application to multiple GCMs (4)	• Assumes constancy of empirical relationships in the future (1,2) • Demands access to daily observational surface and/or upper air data that spans range of variability (5) • Not many variables produced for some techniques (3,5) • Dependent on (usually biased) inputs from driving AOGCM (2)

* Numbers in parentheses under Advantages and Disadvantages indicate that they are relevant to the numbered criteria described. The five criteria are: 1) *Consistency* at regional level with global projections; 2) *Physical plausibility and realism*, such that changes in different climatic variables are mutually consistent and credible, and spatial and temporal patterns of change are realistic; 3) *Appropriateness* of information for impact assessments (i.e. resolution, time horizon, variables); 4) *Representativeness* of the potential range of fututre regional climate change; and 5) *Accessibility* for use in impact assessments.

5 WHAT IS A REGIONAL CLIMATE MODEL?

A regional climate model (RCM) is a high resolution climate model that covers a limited area of the globe, typically 5,000 km x 5,000 km, with a typical horizontal resolution of 50 km. RCMs are based on physical laws represented by mathematical equations that are solved using a three-dimensional grid. Hence RCMs are comprehensive physical models, usually including the atmosphere and land surface components of the climate system, and containing representations of the important processes within the climate system (e.g., cloud, radiation, rainfall, soil hydrology). Many of these physical processes take place on much smaller spatial scales than the model grid and cannot be modelled and resolved explicitly. Their effects are taken into account using parametrizations, by which the process is represented by relationships between the area or time averaged effect of such sub-grid scale processes and the large scale flow.

Given that RCMs are limited area models they need to be driven at their boundaries by time-dependent large-scale fields (e.g., wind, temperature, water vapour and surface pressure). These fields are provided either by analyses of observations or by GCM integrations in a buffer area that is not considered when analysing the results of the RCM (Jones *et al.*, 1995).

The Hadley Centre's current version of the RCM (HadRM3P) is based on HadAM3H, an improved version of the atmospheric component of the latest Hadley Centre coupled AOGCM, HadCM3 (Gordon *et al.*, 2000). HadRM3P has been used with horizontal resolutions of 50 and 25 km with 19 levels in the atmosphere (from the surface to 30 km in the stratosphere) and four levels in the soil. The RCM uses the same formulation of the climate system as in the GCM which helps to ensure that the RCM provides high-resolution regional climate change projections generally consistent with the continental scale climate change projected by the GCM. A full model description is provided in Annex I.

5.1 Issues in Regional Climate Modelling

Model domain

The choice of domain is important when setting up the regional model experiment. A general criterion for the choice of a regional model domain is difficult and the choice depends on the region, the experimental design and the ultimate use of the RCM results (Giorgi and Mearns, 1999). In general the domain should be large enough to allow full development of internal mesoscale circulations and include relevant regional forcings. There are many factors to consider, the important ones for climate change applications being:

- Choose a domain where the area of interest is well away from lateral buffer zone. This will prevent noise from the boundary conditions contaminating the response in the area of interest.
- All the regions that include forcings and circulations which directly affect the fine-scale detail of the regional climate should be included in the domain.
- It is advisable not to place the boundaries over areas of complex terrain to avoid the noise due to the mismatch between the coarse resolution driving data and the high resolution model topography in the interior adjacent to the buffer zone (see **Boundary Conditions** below).
- Whenever possible, place the boundaries over the ocean to avoid possible effects of unrealistic surface energy budget calculations near the boundaries.
- Choose a domain which ensures that the RCM simulation does not diverge from that of the GCM. If this consistency is not maintained then the value of the RCM climate change projections is questionable (Jones *et al.*, 1997).

The Hadley Centre RCM has been run over different regions using different domain sizes in order to explicitly address some of the issues mentioned above: Jones *et al.* (1995) over Europe and Bhaskaran *et al.* (1996) over the Indian subcontinent. The main conclusions from Jones *et al.* (1995) were that in the larger domains, both the main flow and the day-to-day variability in the RCM diverge from that of the GCM on the synoptic scale. At the grid-point scale the RCM freely generates its own features, even in the smaller domains – only at points adjacent to the boundary buffer zone was there evidence of significant distortion by the lateral boundary forcing from the GCM. Results from the domain size experiments of Bhaskaran *et al.* (1996) over the Indian subcontinent contrast strongly with the results over Europe. For the Indian region, even for the largest domain, the variability and main flow in the RCM were strongly correlated with those of the driving GCM. These two studies underscore the importance of considering the inherent dynamics of the region when choosing the model domain. In addition, the importance of the last point was demonstrated in Jones *et al.* (1997) where the domain used allowed the RCM and GCM simulations to diverge in summer. As a result, the RCM climate change projection for summer was very different from, and thus inconsistent with, that in the GCM over large scales.

Resolution

The resolution of the RCM should be high enough to resolve the fine scale detail that characterises regional forcings. The resolution should also be able to provide useful information for specific applications and to capture relevant scales of motion (Giorgi and Mearns, 1999). For example, whereas RCMs at 50 km resolution can provide good simulations of daily precipitation over broad regions of the Alps (Frei *et al.*, 2002) detailed projections for a particular inner Alpine valley would require a much higher resolution. Consideration should also be given to the resolution of the driving model. The study of Denis *et al.* (2003) indicates that with a resolution jump of greater than 12, the large-scale forcing will be too smooth to allow the RCM to generate the full range of fine-scale detail.

The current standard horizontal resolution of HadRM3P is 0.44° x 0.44° lat/long, giving a grid spacing of 50 km. A 25 km resolution version has also been developed and run over Europe in a 30 year climate change experiment. Boundary conditions for the PRECIS RCM are on a grid of 2.5° latitude x 3.75° longitude, about 300 km resolution at 45N or 400 km at the equator.

Initial condition: Spin-up

The initial conditions to start an RCM integration are taken from either a driving GCM or from re-analysis of observations. The predictability limits of deterministic weather forecasting mean that the atmospheric component of these will be forgotten within a few days. However, the initial state of the soil variables in the land-surface model can be important as it may take one or more annual cycles for these to come into equilibrium with the atmospheric forcing. In this case simulations of surface temperature, precipitation and related variables could be biased within this spin-up period.

The Hadley Centre RCMs take about one year to spin up and this part of the simulation is regarded as unrealistic as the implied lack of equilibirum is unphysical. As a result, data from the spin-up period is ignored for purposes of climate scenario generation.

Boundary conditions

- Lateral boundary conditions
  There are two common methods used to drive the regional model:
  – Relaxation method (Davies and Turner, 1977): Application of a Newtonian term which drives the model solution toward the large-scale driving fields over a lateral buffer zone. The forcing term is multiplied by a weighting factor.
  – Spectral nesting (Kida *et al.*, 1991 and Sasaki *et al.*, 1995): The large-scale driving fields force the low-wavenumber component of the solution throughout the entire domain, while the regional model solves the high-wavenumber component.

The main variables comprising the lateral boundary conditions for RCMs (including most Hadley Centre RCMs) are atmospheric pressure at the surface and horizontal wind components, temperature and humidity through the depth of the atmosphere. Also, for projecting climate change, the PRECIS RCM includes a representation of the sulphur cycle and so the relevant chemical species are also required as boundary conditions. The Hadley Centre uses the relaxation technique and is implemented across a four-point buffer zone at each vertical level. Values in the RCM are relaxed towards values interpolated in time from data saved every 6 hours from a GCM integration. Results from Hassell and Jones (2004) and Hudson and Jones (2002) indicate that the higher resolution of an RCM can generate realistic transient large-scale features (e.g. tropical cyclones) that are absent from the GCM. These do not lead to significant deviations from the large-scale mean climate of the GCM but are important for accurate simulation of the local climate of parts of the region. Such features would generally not evolve with the use of spectral nesting.

- Surface boundary conditions
  Most RCMs developed to date include representations of the atmosphere and the land surface only. As a result, they need to be supplied with surface boundary conditions over the oceans which consist of sea-surface temperatures (SSTs) and, where appropriate, information about the extent and thickness of sea-ice. (In some cases the land-surface model also requires a boundary condition of temperature of the bottom soil layer.) If this information is taken directly from a coupled GCM then its coarse resolution means that there could be quite large regional errors in the data, and for coastal points and inland seas they may have to be interpolated or extrapolated which could lead to even larger errors locally. An alternative is to use observed values (at higher resolution) for the GCM and RCM simulations of present-day climate and then obtain values for the future by adding on changes in the SSTs and sea-ice extent and thickness from a coupled GCM.

The Hadley Centre has used the second of the above approaches. Observed SSTs and sea-ice (on a 1° grid) are used with an atmosphere-only GCM for the present-day simulation (which then provides lateral boundary conditions for the RCM present-day simulation). This helps to provide a better simulation of

the large-scale climate over many regions. For the future climate, changes in SSTs and sea-ice derived from a coupled GCM simulation are added to the observed values to give the lower boundary forcing for the atmospheric GCM and RCM simulations.

Simulation length

In order to investigate the state of the regional climate, the length of the simulation should be at least 10 years to give a reasonable idea of the mean climate change, although 30 years is preferable to better determine changes in higher order statistics. This is particularly important for the analysis of aspects of climate variability, such as distributions of daily rainfall or climate extremes.

In a study with a previous version of the Hadley Centre RCM, Jones *et al.* (1997) have shown that a 10-year simulation captures about half of the variance of the true regional climate change response (i.e. that obtained with a simulation of infinite length). This should thus be regarded as the minimum length needed to obtain an estimate of the climate change signal. To capture 75% of the variance of the true signal, a 30-year simulation is required. In a more recent study, Huntingford *et al.* (2003) showed that with 20-30 year simulations, statistically significant changes in extreme precipitation could be obtained.

Representation of physical processes

Errors in regional climate simulations derive both from the lateral boundary forcing and the model formulation (Noguer *et al.*, 1998).

In general there are two approaches regarding the formulation of an RCM:

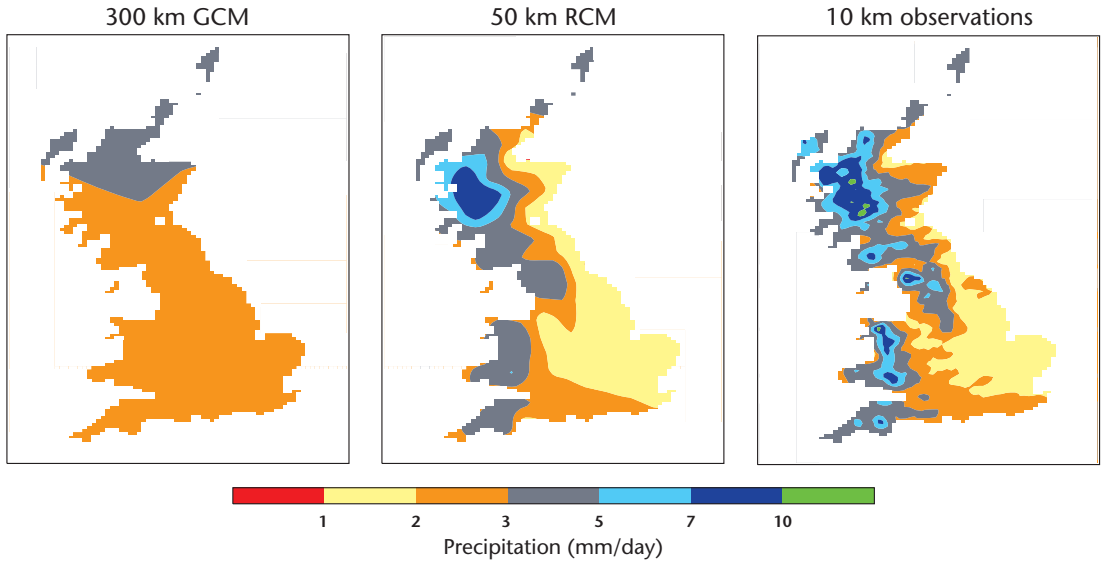
- Use of different formulations for the nested and driving models. Advantage: each model is developed and optimised for the respective resolution (and region in the case of the RCM). Disadvantage: any differences in the GCM and RCM could be caused by the different formulations, and so it is less clear that the RCM projection can be interpreted as a high-resolution version of the GCM projection.
- Use of the same formulation in the nested and driving model. Advantage: maximum compatibility and use of a formulation designed to perform well over all (current) climatic conditions. Disadvantage: any resolution dependency in the model formulation will need to be corrected or may lead to biases.

The Hadley Centre RCM and the GCM employ identical representations of both the grid scale dynamics and the sub-grid scale physics with account taken for those which are dependent on resolution. In this way, the RCM produces high resolution projections for a region which are consistent with the large-scale projections from the GCM.

5.2 How regional climate models add value to global climate models

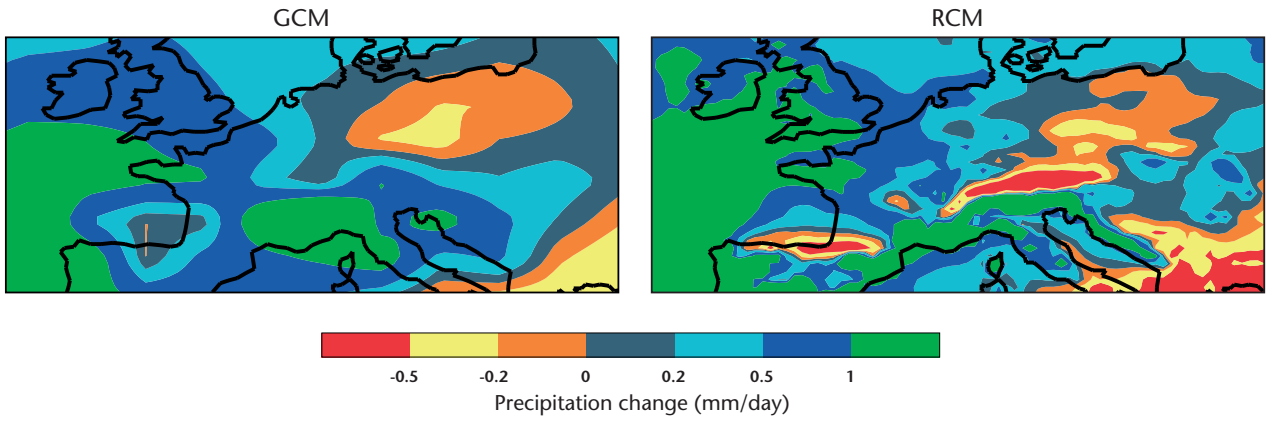
RCMs simulate current climate more realistically

Where terrain is flat for thousands of kilometres and away from coasts, the coarse resolution of a GCM may not matter. However, most land areas have mountains, coastlines, etc., on scales of 100 km or less, and RCMs can take account of the effects of much smaller scale terrain than GCMs. The diagram below shows simulated and observed winter precipitation over Great Britain. The observations clearly show enhanced rainfall over the mountains of the western part of the country, particularly the north west. This is missing from the GCM simulation, which shows only a broad north–south difference. In contrast to the GCM, the 50 km RCM represents the observed rainfall pattern much more closely.



RCMs project climate change with greater detail

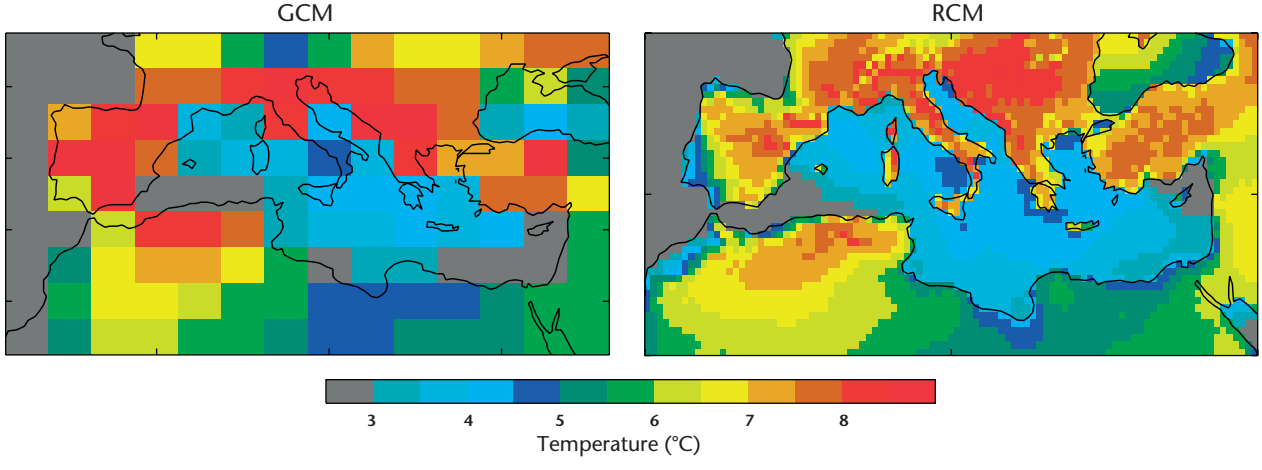
The finer spatial scale will also be apparent, of course, in projections. When warming from increased greenhouse gases changes the patterns of wind flow over a region then the way mountains and other local features interact with this wind flow pattern will also change. This will affect the amount of rainfall and the location of windward rainy areas and downwind rain-shadow areas. For many mountains and even mountain ranges, such changes will not be seen in the GCM, but the finer resolution of the RCM will resolve them. The diagram below shows how the RCM predicts that winter precipitation over the Pyrenees and Alps, two mountain ranges in Europe, will decrease substantially between now and the 2080s. The GCM for the same period shows there to be little change, or even an increase in rainfall over these areas.



RCMs represent smaller islands

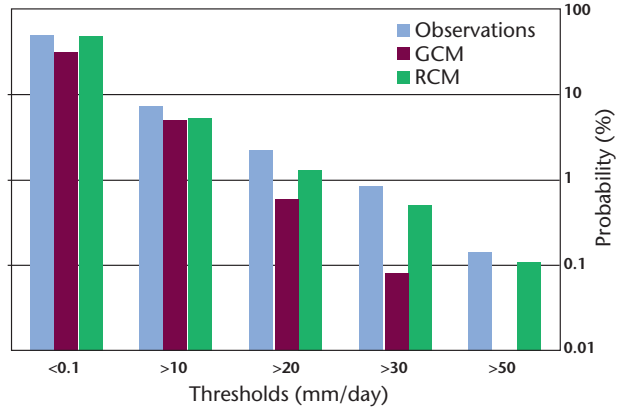
The coarse resolution of a GCM means than many islands are just not represented and, hence, their climate is projected to change in exactly the same way as surrounding oceans. However, land surface has a much lower thermal inertia than the oceans and will warm faster. If the land surface has any significant hills or mountains, these will have a substantial influence on rainfall patterns. In an RCM, many more islands are resolved, and the changes projected can be very different to those over the nearby ocean.

As an example, the diagram below shows the Hadley Centre GCM projection of summer temperature change in and around the Mediterranean. Even large islands such as Corsica, Sardinia and Sicily (not forgetting peninsular Italy) are not seen by the GCM, and hence they appear to warm at the same rate as the sea. In contrast, in the corresponding RCM simulation, these islands are resolved and are seen to warm faster than the surrounding ocean, as might be expected. Hence, impacts based on the GCM will be in error. (Of course some islands will not even be resolved at a resolution of 50 km, and await the use of the RCM at a higher resolution.)



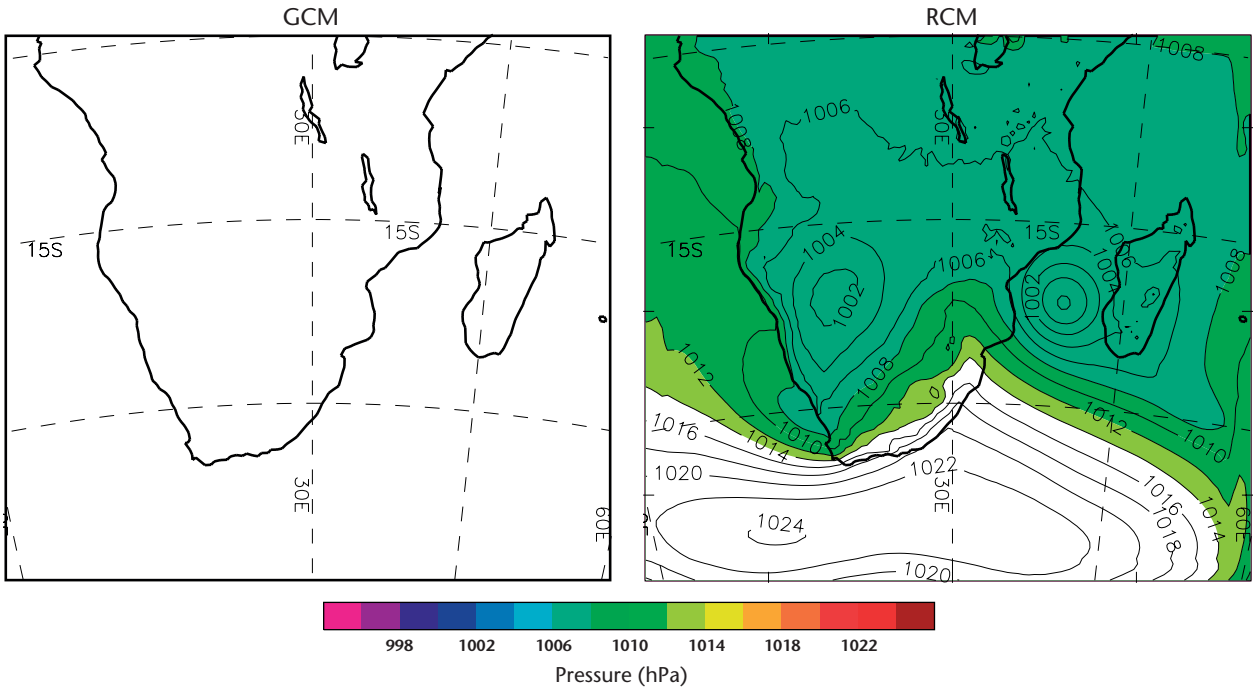
RCMs are generally much better at simulating and projecting changes to extremes

Changes in extremes of weather, for example heavy rainfall events, are likely to have more of an impact than changes in annual or seasonal means. RCMs are much better than GCMs at simulating extremes. The diagram opposite (right) shows the probability of daily rainfall over the Alps being greater than a number of thresholds up to 50 mm. It is clear that the GCM-simulated probability does not agree well with observations, whereas the RCM simulation is much more realistic. For this reason, RCM projections of changes in extremes in the future are likely to be very different to, and much more credible than, those from GCMs.



RCMs can simulate cyclones and hurricanes

The impact of a hurricane (severe tropical cyclone, typhoon), such as Hurricane Mitch that hit Central America in October 1998, can be catastrophic. We do not know if hurricanes will become more or less frequent as global warming accelerates, although there are indications that they could become more severe. The few hundred kilometre resolution of GCMs does not allow them to properly represent hurricanes, whereas RCMs, with their higher resolution, can represent such mesoscale weather features. This is clearly illustrated below, where the pressure pattern for a particular day simulated by both a GCM and the corresponding RCM are shown. At first glance, the two pressure patterns look very similar though there is one crucial difference; there is a cyclone in the Mozambique Channel in the RCM which is absent in the driving GCM.



6 PRECIS

6.1 What is PRECIS?

PRECIS is a regional modelling system that can be run over any area of the globe on a relatively inexpensive, fast PC to provide regional climate information for impacts studies.

The idea of constructing a flexible regional modelling system originated from the growing demand of many countries for regional-scale climate projections. Only a few modelling centres in the world have been developing RCMs and using them to generate projections over specific areas as this task required a considerable amount of effort from an experienced climate modeller and large computing power. Both these factors effectively excluded many developing countries from producing climate change projections and scenarios. The Hadley Centre has configured the third-generation Hadley Centre RCM so that it is easy to set up. This, along with software to allow display and processing of the data produced by the RCM, forms PRECIS.

6.2 Who should use PRECIS?

PRECIS is a flexible, easy-to-use and computationally inexpensive RCM designed to provide detailed climate scenarios. However, the human and computational resources to use the model are not insignificant, especially in the developing countries at which it is aimed. PRECIS will not be applicable to all countries. The following factors should be considered when considering using PRECIS:

1) In the standard PRECIS set-up, there is an implicit maximum resolution of 25 km and thus countries or regions (e.g. islands) smaller than this will not be resolved (although there is always the option of specifying land points for land areas which approach this scale; see the companion technical manual (Wilson *et al.*, 2004), Chapter 4).
2) In order to check at the local level that the PRECIS model is providing realistic information, it is desirable to have good observations of the climate relevant to the region or application for which PRECIS is being used.
3) In addition to the basic computing resource of one or more fast PCs, it is useful to have a reliable power supply and necessary to have expertise to maintain these hardware and support systems.
4) Running the model, and interpreting and disseminating results from the PRECIS experiments, will require time allocated from people with relevant experience (although the training materials and the activities in the PRECIS workshops run by the Hadley Centre will provide much useful information to those with the right background).
5) PRECIS experiments require several months to run, so PRECIS cannot be used to provide instant climate scenarios.

6.3 Description of PRECIS components

The components of PRECIS come under the following six main categories:

1) User interface to set up RCM experiments
2) The latest Hadley Centre RCM
3) Data-processing and graphics software
4) Boundary conditions from re-analysis and the latest Hadley Centre GCM
5) Training materials and PRECIS workshop
6) PRECIS website and help-desk

The first three categories are described in separate sections below. The boundary conditions for the PRECIS RCM are clearly an integral part of the system, but as they comprise a very large amount of data (20-30 Gbytes for a 30-year simulation) they have to be supplied separately. They are stored online at the Hadley Centre and will be made available on request (please see contact details on the inside back cover of this handbook). The data will be supplied on a storage medium specified by the user. The Hadley Centre is currently adding a facility to use boundary conditions from two other GCMs and hopes to extend this range through negotiation with other global modelling centres. More detailed information on these four components is given in the companion PRECIS technical manual.

The training materials provide some of the scientific background and all the technical instructions necessary for productive and informed use of the PRECIS RCM to construct climate scenarios for impacts assessments. These materials comprise this handbook and the accompanying technical manual. The workshops comprise a series of formal presentations, practical sessions and open sessions for discussion of issues, project planning or other subjects relevant to the participants. The formal presentations provide more depth on the material contained in, and relevant to, the handbook and include material on the science of climate change and the construction and use of climate scenarios. The practical sessions deal with the installation of PRECIS and allow participants to gain experience in configuring, running and analysing PRECIS experiments. The open sessions provide opportunities for participants to discuss their workplans and interests, plan future collaborations and raise and discuss issues relevant to the use of PRECIS or other approaches for generating and using climate scenarios.

Finally, the other materials and resources that are available are a website with information about PRECIS and current developments, relevant literature, documentation and activities and a help desk to contact for specific advice and assistance. For details of the website and help desk please see the inside back cover of this handbook.

6.4 The PRECIS User Interface

When PRECIS is started on the PC, the user is presented with a graphical menu to allow the setting up of the RCM experiment. It comprises five main functions: 1) setting up the region (domain) over which the experiment will be performed; 2) the emissions scenario being used in the experiment; 3) the period over which the experiment will be run; 4) the data that the experiment will produce; and 5) the running of the experiment. The first function is provided by graphical interfaces, which allow first a model domain to be drawn around the region of interest, and then detailed specification of land and sea points with respect to a very high-resolution coastline map. The second function is provided by a simple graphical interface, which displays four SRES emissions profiles (A1FI, A2, B2 and B1). The third function allows the choice of the start and end month and year of the experiment. The fourth function provides the user with a series of choices about data which will be output by the RCM to allow monitoring of the experiment as it runs and for later analysis and processing.

Once the experiment has been defined by these four functions, the model projection can then be started using the model execution function. As the tests and the running of the RCM will be done in experiments which may take from hours to days to weeks, this function also provides for the experiment to be interrupted. This allows the user to stop the experiment in a controlled manner given of order half an hour's notice. For unforeseen hardware or operating system problems, such as loss of power or accidental switching off of the PC, a checkpoint is saved every eight to twelve real hours (depending on speed of simulation), from which the model may be re-started.

6.5 The PRECIS Regional Climate Model

The PRECIS climate model is an atmospheric and land surface model of limited area and high resolution which is locatable over any part of the globe. Dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, the land surface and the deep soil are all described. Boundary conditions are required at the limits of the model's domain to provide the meteorological forcing for the RCM. Information about all the climate elements as they evolve through being modified by the processes represented in the model is produced. For a detailed description of the model components, please see Annexe I of this handbook.

Dynamical flow

Meteorological flow and thermodynamics are modelled throughout the atmosphere. Special consideration is given to the model formulation in the boundary layer and account taken of the modifying effects of mountains.

Atmospheric Sulphur Cycle

The distribution and life cycle of sulphate aerosol particles is simulated throughout the atmosphere. Background concentrations and emissions of sulphur dioxide (both natural and man made) are necessary, as are those for chemical species intrinsic to the sulphur cycle.

Clouds and Precipitation

Convective clouds and large scale clouds (e.g. stratocumulus) are treated separately in their formation, precipitation and radiative effects.

Radiative Processes

Radiative processes are modelled to be dependent on atmospheric temperature and humidity, concentrations of radiatively active gases, concentrations of sulphate aerosols and clouds. The seasonal and daily varying cycles of incoming solar radiation are also included.

Land Surface and Deep Soil

The land surface has a vegetated canopy which interacts with the flow, incoming radiation and precipitation and provides fluxes of heat and moisture to the atmosphere and rainfall runoff. Beneath the surface, deep soil temperature and water content are simulated.

Boundary Conditions

The model requires surface boundary conditions and lateral boundary conditions at the model's edges. Surface boundary conditions are only required over ocean and inland water points, where the model needs timeseries of surface temperatures and ice extents. Lateral boundary conditions provide the necessary dynamical atmospheric information at the latitudinal and longitudinal edges of the model domain; namely surface pressure, winds, temperature and humidity and the necessary chemical species when the sulphur cycle is being modelled. There is no prescribed constraint at the upper boundary of the model (except for the input of solar radiation).

Model Outputs

A full range of meteorological variables can be diagnosed by the model. Predefined comprehensive sets of output variables, available at different temporal resolutions, are provided to allow experiments for

standard purposes to be configured quickly. Advanced users will have some choice over the frequency and areal and vertical extent of output data.

6.6 PRECIS data-processing and graphics software

The main PRECIS display system has been developed from CDAT, public-domain software developed by PCMDI (Programme for Climate Model Diagnosis and Intercomparison, LLNL, California, US). CDAT is also supplied as part of the PRECIS system as it has been developed specifically for processing and displaying climate data, and is thus particularly suitable for this application. The system also includes GrADS, another public-domain software package which is widely used in the meteorological and climate research community for processing and displaying data. Functionality additional to that available in the standard GrADS distribution allows the display of data on grid of the PRECIS RCM which, in general, will be a rotated pole latitude longitude grid. The PRECIS system also has the facility to convert model data into formats compatible with both of these software packages, netCDF and GRIB, which are the two standard formats for meteorological and climate data.

7 CREATING REGIONAL CLIMATE SCENARIOS FROM PRECIS

Section 2 explained that climate scenarios can inform impacts studies for assessing climate change vulnerabilities and adaptation. Techniques for adding the regional detail generally required in these assessments were discussed in Section 4. In this section, we explore issues associated with the application of the particular technique used in PRECIS to provide the climate information required for the impacts models. This is essentially a three-stage process comprising:

1) running the PRECIS RCM over the area of interest to provide simulations of a recent climate period (e.g. 1961-90), and comparing these with observations, to validate the model;
2) running the PRECIS RCM to provide climate change projections for the region of interest; the regional model is supplied with GCM fields from the Hadley Centre, although the system is being developed to use fields from other climate models; and
3) deriving relevant climate information from these projections guided by an understanding of the needs of the impacts models and an assessment of the climate models' performance and projections.

7.1 Validation of the PRECIS RCM

A measure of the confidence to be placed on projections of climate change from a particular climate model (whether global or regional) comes in part from its ability to simulate recent climate. With PRECIS, this validation can be done in two ways.

a) The RCM is run for a recent climate period (e.g., 1961-90; this run is also required for projections of climate change, see below) and the results are compared with a climatology formed from observations over the same period. Comparisons should include at least statistics of annual or seasonal means (e.g. summer precipitation) and probably other measures e.g., as a more stringent test, frequency distribution of quantities such as daily temperature over a specific grid square.
b) The RCM is driven, not by output from a GCM, but by a re-analysis of actual global observations over the same time period. The re-analysis uses a weather forecasting (NWP) model, taking in observational data and assimilating it to provide the optimum estimate of the state of the atmosphere on any given day (or shorter time interval, e.g. 6 hours). Comparison of the model simulation can then be made with day-to-day observations for the same time, providing a more rigorous test of the model.

Needless to say, no model will give a perfect validation against climatology or observations. It is best to validate two or more climate models (GCM or RCM) to enable a choice to be made of the most appropriate model to be used in scenario generation for that region. Also, it is important to include in the validation any variables which will be used for impacts studies and to determine reasons for any biases identified.

7.2 Generating climate change projections

The coupled ocean-atmosphere GCMs used as the starting point for regional climate projections are usually run in "transient" mode, i.e. taking gradually increasing greenhouse gas concentrations (observed and projected) and calculating the resulting evolution of the climate. Typically, this is done over periods of 240 years, from 1860 to 2100, with observed concentrations used for the period 1860-2000, and future concentrations calculated from one or more emissions scenarios. This type of long transient run is not performed with RCMs because of the computational expense; instead the RCM is usually driven with a "time-slice" of 10-30 years output from the GCM to provide good statistics on climate change for particular periods of interest.

To generate climate change projections, two such time periods are used to drive the RCM. The first period may be when there are no increases in emissions (i.e. to represent pre-industrial climate) or can be for a recent climate period. 1961-1990 is often chosen as it is the current World Meteorological Organization (WMO) 30-year averaging period. The second period can be any period in the future, although will often be taken at the end of the century (e.g., 2071-2100) when the climate change signal will be clearest against the noise of climate variability.

7.3 Providing a wide range of projections of possible future climates

Scenarios of climate change are usually needed for a number of different time periods in the future (e.g. 2041-2070) and corresponding to a number of emissions scenarios (e.g., the IPCC SRES B2 and B1). Of course, regional model runs could be undertaken for each period separately, and for each emissions scenario separately, but this would require a substantial amount of computing resources (similar to that used in running the original GCM experiments).

An alternative is to undertake a regional model projection for the most distant time period needed (2071-2100) and for a high emissions scenario (for example, SRES A2). This will give a clear signal of climate change against the noise of natural variability providing robust patterns of change in, for example, winter precipitation or summer temperature. These patterns can then be scaled (i.e. interpolated or extrapolated) to correspond to other time periods and emissions scenarios (e.g. Mitchell, 2000). The scaling factors used can be derived from GCMs as they have a full transient response from 1860-2100 and can

comprise such variables as global mean annual mean temperature. Global temperature rises from the Hadley Centre HadCM3 model are shown in Table 3 below; these can be used to give scaling factors referenced to the 2080s under A2 emissions, if those are the conditions under which the RCM simulation was run. Other climate models will give different factors. Clearly, this technique produces an additional level of uncertainty, particularly for spatially variable quantities like precipitation and for cases of inhomogeneous forcing. This is discussed in Chapter 13 of the IPCC WGI TAR (Mearns *et al.*, 2001).

	2020s	2050s	2080s
SRES B1 emissions	0.79	1.41	2.00
SRES B2 emissions	0.88	1.64	2.34
SRES A2 emissions	0.88	1.87	3.29
SRES A1FI emissions	0.94	2.24	3.88

Table 3: *HadCM3 global temperature change (difference from 1961-1990) for different time periods and different emissions scenarios.*

In order to provide a comprehensive range of possible future climates, results from a range of GCMs should be considered, as their projected large-scale changes may differ. Currently, GCMs have the advantage that there are several of them which have been used to make projections of global climate change under IPCC SRES emissions, and hence some idea of the uncertainty in change at any location can be gained by looking at the spread of GCM results, albeit at low resolution. The PRECIS RCM has not yet been driven by several GCMs, so we cannot estimate the range in the detailed regional projections in this way. This idea is currently being pursued to a limited extent with PRECIS and in the European Commission project Prudence (http://www.dmi.dk/f+u/klima/prudence/).

7.4 Creating regional climate change scenarios for use in impacts models

Socio-economic impact models (e.g., predicting crop yield or water resources) used to assess the impacts of climate change require climate information from those periods between which the change is being estimated. These periods usually represent the present or recent past, and some period in the future. There are two different approaches to obtain this information. The most common approach is to use observed current climate information. The impacts models will reproduce the current or recent past situation better when using observed climate as an input, rather than model-simulated climate, as there are often significant biases in the model control simulations. The required future climate information is then created by combining ***changes*** derived from the model simulations of the present and future climate with the observed "baseline" climate. This approach has the advantage of avoiding errors in model-simulated current climate. However, there are many ways in which the future climate information may be derived. The simplest approach is just to add an average spatial pattern of change derived from the model onto the observed data, although even for a basic variable such as precipitation it is not clear whether absolute or percentage increments are more appropriate. If more detailed climate information is required, for example if climate variability is important, then there is a range of possibilities (see e.g. Arnell *et al.*, 2003).

The second approach is to use climate model data for both periods (recent and future). Then, the difference between the two responses will represent the impact of climate change in that sector. With improvements in control simulations, which are now being realised with improved models and the use of higher resolution, this approach is becoming increasingly attractive. It is conceptually simpler and allows direct application of the changes in all statistical moments provided by the climate change projection.

When selecting a method for providing the climate information to the impacts model, knowledge of the performance of the climate model and an assessment of the projected climate changes is invaluable. For example, in Arnell *et al.* (2003), absolute projected rainfall decreases for some areas were sometimes larger than the observed rainfall and so applying proportional changes to the observed baseline was the only sensible approach. Also, in some regions, cloud cover was overestimated compared to observations - which may imply that changes in shortwave radiation reaching the surface would be underestimated. When developing scenarios from RCM experiments for use in impacts models it also would be desirable to develop the scenarios from the coarse-scale driving model (when possible). This will allow comparison of the effect of the difference in spatial scale of scenarios on the impacts (e.g. Arnell *et al.*, 2003) and will provide more information on the sensitivity of the impacts model to different inputs.

7.5 Example: Generating climate change scenarios for the UK from RCM projections

An example of one approach that uses several climate models is the new climate change scenarios for the UK (Hulme *et al.*, 2002). The RCM was used to make three simulations of recent climate (1961-90) and three projections of change (2071-2100) arising from the IPCC SRES A2 emissions. Scenarios for other 30-year periods (2011-2040; 2041-2070) and other emissions (SRES A1FI, B2 and B1) were generated by pattern scaling as described in Section 7.3. Seasonal mean climate change in a number of quantities, for these periods and emissions, were shown in the report as maps (see Figure 5 and http://www.ukcip.org.uk/). Information about more detailed changes, e.g. in the distribution of daily maximum temperatures or rainfall, were presented as directly calculated from the models.

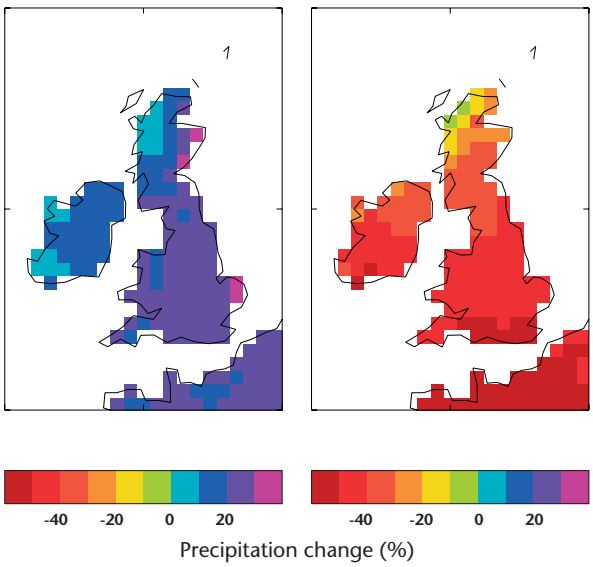


Figure 5: *Percentage changes in winter (left) and summer (right) rainfall projected at 50 km resolution, due to the A2 emissions scenario, for the period (2071-2100) minus (1961-1990).*

In addition to RCM output, data from nine different GCMs (each run with IPCC SRES A2 emissions) was accessed. These results (for seasonal temperature and precipitation) were illustrated in the report, and the spread of GCM projections over the UK was used to make an informed judgement of model-based uncertainty, which in turn was then applied to the RCM scenarios. This is far from ideal, but represents a reasonable way forward at this time of very limited SRES-driven RCM results over the area. Note that no attempt was made to judge the relative performance of the GCMs.

Examples of climate change scenarios using Hadley Centre RCMs over other parts of the world (Indian subcontinent and southern Africa) are shown in Annex II, and the application of the southern Africa scenarios to look at change in hydrology is shown in Annex III.

8 FURTHER DEVELOPMENTS

This PC-based regional climate modelling system, PRECIS, is a step forward in making climate modelling and climate scenario generation more readily accessible, particularly to developing countries. Developments which will make the system more useful are planned over the next few years.

- The first (in 2004) will be the ability to drive the PRECIS RCM with output from other GCMs, thus allowing this aspect of "science uncertainty" to be explored.
- One specific way of estimating this science uncertainty is to run large ensembles of related GCMs, each of which is derived by perturbing some of the parameters in the model by physically reasonable amounts. The Hadley Centre is currently constructing such an ensemble and data from these experiments will be made available to drive PRECIS.
- The Hadley Centre GCM which is used to drive the PRECIS RCM will continue to be improved, by increasing its resolution (both horizontally and vertically), by improving the representation of processes in all parts of the climate system, and by including new processes that provide feedbacks into climate change (for example, the carbon cycle and atmospheric chemistry). Improvement in GCMs may be the best way to improve projections from RCMs.
- The PRECIS RCM will itself be improved, in similar ways to the GCM, by improving the model formulation and also by increasing its resolution, initially to 10 km. Currently, when used at 25 km, the PRECIS RCM runs about 6 times slower than at 50 km (for a given area), so the practical application of the higher resolution awaits faster PCs. However, PC speeds are increasing at a rapid rate, and hence this limitation will become less and less severe.
- Currently the PRECIS RCM does not include a regional ocean model. The Hadley Centre is in the process of developing regional ocean models which will be able to be coupled to the new generation of atmospheric RCMs. Initial tests with the coupling of one ocean model will be undertaken this year and the aim is to make a coupled RCM available in a future release of PRECIS.
- Between each major release of PRECIS smaller, incremental improvements or new functionality will be incorporated. These will be made available automatically to new users of PRECIS and existing users will be informed of them and provided with the necessary updates if they request them. For example, the ability to modify the default vegetation specified in the RCM will be made available to new users from June 2004. This will allow the RCM to represent realistic vegetation on smaller islands and enable the running of sensitivity experiments to assess the effects of changes in vegetation e.g. consistently with future economic scenarios or as a predicted consequence of future climate change.

ANNEX I: DESCRIPTION OF THE PRECIS REGIONAL CLIMATE MODEL (RCM)

The PRECIS RCM is an atmospheric and land surface model of limited area and high resolution which is locatable over any part of the globe. Dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, the land surface and the deep soil are all described and information from every aspect is diagnosed from within the model.

The model requires prescribed surface and lateral boundary conditions. Surface boundary conditions are only required over water, where the model needs timeseries of surface temperatures and ice extents. Lateral boundary conditions provide dynamical atmospheric information at the latitudinal and longitudinal edges of the model domain. There is no prescribed constraint at the upper boundary of the model. The lateral boundary conditions comprise the standard atmospheric variables of surface pressure, horizontal wind components and measures of atmospheric temperature and humidity. Also, as certain configurations of the PRECIS RCM contain a full representation of the sulphur cycle, a set of boundary conditions (including sulphur dioxide, sulphate aerosols and associated chemical species) are also required for this. These lateral boundary conditions are updated every six hours; surface boundary conditions are updated every day.

The model is described in three main sections: the dynamics, the sulphur cycle and the physical parameterizations. The dynamics deals with the advection of the meteorological state variables (i.e. those required for lateral boundary conditions), which are consistently modified by the physical parameterizations: clouds, precipitation, radiation, boundary layer, surface exchanges and gravity wave drag. The sulphur cycle is also a physical parameterization, but one whose state variables (concentrations of chemical species) are treated as prognostic and advected as tracers.

The PRECIS RCM is based on the atmospheric component of HadCM3 (Gordon *et al.*, 2000) with substantial modifications to the model physics, which are marked with a double asterisk (**) where they occur.

I.1 Atmospheric Dynamics

The atmospheric component of the PRECIS model is a hydrostatic version of the full primitive equations, i.e. the atmosphere is assumed to be in a state of hydrostatic equilibrium and hence vertical motions are diagnosed separately from the equations of state. It has a complete representation of the Coriolis force and employs a regular latitude-longitude grid in the horizontal and a hybrid vertical coordinate. There are 19 vertical levels, the lowest at ~50m and the highest at 0.5 hPa (Cullen, 1993) with terrain-following σ-coordinates (σ = pressure/surface pressure) used for the bottom four levels, purely pressure coordinates for the top three levels and a combination in between (Simmons and Burridge, 1981). The model equations are solved in spherical polar coordinates and the latitude-longitude grid is rotated so that the equator lies inside the region of interest in order to obtain quasi-uniform grid box area throughout the region. The horizontal resolution is 0.44°x0.44°, which gives a minimum resolution of ~50 km at the equator of the rotated grid. Due to its fine resolution, the model requires a timestep of 5 minutes to maintain numerical stability.

The prognostic variables in the dynamical, layer cloud and boundary layer schemes are surface pressure (p^*), zonal and meridional wind components (u and v), potential temperature adjusted to allow for the latent heat of cloud water and ice (Θ_L), and water vapour plus liquid and frozen cloud water (q_T). In addition, there are five chemical species which are used to simulate the spatial distribution of sulphate aerosols.

An Arakawa B grid (Arakawa and Lamb, 1977) is used for horizontal discretization to improve the accuracy of the split-explicit finite difference scheme. In this horizontal layout, the momentum variables (u and v) are offset by half a grid box in both directions from the thermodynamic variables (p^*, Θ_L, q_T). The aerosol variables also lie on the thermodynamic grid. Geostrophic adjustment is separated from the advection part of the integration: adjustment is iterated three times per 5 minute advection timestep. Averaged velocities over the three adjustment timesteps are used for advection, which is integrated in time using the Heun scheme (Mesinger, 1981). This finite difference scheme is 4th order accurate except at high wind speeds when it is reduced to 2nd order accuracy for stability. The numerical form of the dynamical equations formally conserves mass, momentum, angular momentum and total water in the absence of source and sink terms. Physical parameterizations and numerical diffusion are represented by three-dimensional source and sink vector functions of the prognostic variables.

Horizontal diffusion is applied everywhere to the wind, Θ_L and q_T fields in order to represent unresolved sub-grid scale processes and to control the accumulation of noise and energy at the grid scale. Fourth order diffusion (∇^4) is used throughout, except on the top level for the winds and Θ_L, where second order diffusion (∇^2) is applied. The order of diffusion and diffusion coefficients are resolution- and timestep-dependent**.

I.2 Sulphur Cycle**

The model requires five prognostic variables to simulate the distribution of sulphate aerosol. These are mass mixing ratios of gaseous sulphur dioxide (SO_2), dimethyl sulphide (DMS) and three modes of sulphate aerosol (SO_4). The sulphate modes represent sulphate dissolved in cloud droplets plus two free particle modes assumed to possess log-normal size distributions: the Aitken mode (mean radius 24 nm) is produced by gas-phase oxidation of SO_2 followed by particle nucleation and the accumulation mode (mean radius 95 nm) is largely the result of processing by clouds of activated aerosol particles via the dissolved mode. The model simulates transport of each of the five variables via horizontal and vertical advection, convection and turbulent mixing. The oxidation of DMS to SO_2 and SO_2 to sulphate is calculated from prescribed monthly mean three-dimensional fields of hydroxyl radical (OH), hydrogen peroxide (H_2O_2) and the peroxide radical (HO_2) obtained from simulations of the Lagrangian chemistry model STOCHEM (Collins *et al.*, 1997). The model converts DMS to SO_2 in the presence of OH, while the conversion of SO_2 to sulphate proceeds via oxidation by OH in the gas phase and oxidation by H_2O_2 in the aqueous phase. The latter reaction is a significant sink of H_2O_2 which is replenished gradually to its prescribed concentration at a rate dependent on the prescribed concentration of HO_2, using the reaction rate employed in the STOCHEM model.

I.3 Physical parameterizations

I.3.1 Clouds and Precipitation

Large scale

Layer cloud cover and cloud water content (liquid and frozen phases being partitioned by a statistical temperature function) in a grid box are both calculated from a saturation variable, q_C, defined as the difference between total water, q_T, and the saturation vapour pressure. It is assumed that the sub-grid scale distribution of q_C can be represented by a symmetrical triangular function (Smith, 1990). Where RH_{crit} represents the grid box mean relative humidity (RH) above which cloud begins to form, the grid box cloud fraction (C) is represented by a quadratic spline passing through the points in the (RH, C) plane (RH_{crit}, 0), (1, 0.6)** and (1+RH_{crit}, 1).

Values of RH_{crit} are calculated for each grid box at every timestep** to represent the effects of unresolved sub-grid scale motions on the distribution of q_T within a model grid box. This parameterization is dependent upon the standard deviations of q_C within a model grid box and its eight neighbours in the horizontal and pressure, but has no geographical or time dependencies. Layer cloud volume is calculated in three equally spaced sub-gridbox vertical levels by a separate cloud volume calculation in each partition. The horizontal cloud area fraction for the gridbox is then taken from the maximum sub-grid value.

Cloud water is assumed to be liquid above 0°C, frozen below -9°C and a mixture in between; the threshold values of cloud liquid water for precipitation formation are $1.0x10^{-3}$ (kg/kg) over land** and $2.0x10^{-5}$ over sea**. Layer cloud can form at any level except the top of the stratosphere (level 19). Large scale precipitation from layer cloud is dependent on cloud water content, with allowance made for the greater efficiency of precipitation when the cloud is glaciated. The evaporation of large scale precipitation is accounted for, as are enhanced precipitation rates via seeding from layers above. Large scale precipitation within a grid box is assumed fall on 75% of the land surface**, regardless of layer cloud fraction.

Convective

A mass flux penetrative convective scheme (Gregory and Rowntree, 1990) is used with an explicit downdraught (Gregory and Allen, 1991) and includes the direct impact of vertical convection on momentum (in addition to heat and moisture) (Gregory *et al.*, 1997). The initial mass flux of the plume is empirically related to the stability of the lowest convecting layers. Mixing of convective parcels with environmental air and forced entrainment and detrainment are also modelled.

Convective precipitation does not change phase if the associated latent cooling would take the temperature below the freezing point again. The evaporation of convective precipitation is accounted for. Convective precipitation within a grid box is assumed fall on 65% of the land surface**, regardless of convective cloud fraction. The threshold values of cloud liquid water for precipitation are 2g/kg over land and 0.4g/kg over sea.

I.3.2 Radiation

The radiation scheme includes the seasonal and diurnal cycles of insolation, computing short wave and long wave fluxes which depend on temperature, water vapour, ozone (O_3), carbon dioxide (CO_2) and clouds (liquid and frozen water being treated separately), as well as a package of trace gases (O_2, N_2O, CH_4, CFC11 and CFC12). The calculations are split into 6 short wave bands and 8 long wave bands.

Cloud overlaps are calculated by the maximum-random overlap method, wherein clouds in contiguous layers are assumed to be maximally overlapped, whereas clouds in non-contiguous layers overlap randomly. The model distinguishes between convective and large-scale (or stratiform) cloud maximum-random overlap and thus maintains the vertical coherence of convective cloud.

The radiative representation of anvils** modifies the convective cloud amount (CCA) to vary with height during deep convection. The CCA is reduced by a constant factor from the cloud base to the freezing level. Clouds have to be more than 500 hPa deep to be modified by the anvil scheme. Convective cloud fraction in the presence of deep convection is increased linearly with model level from the freezing level to the cloud top to represent the anvil, and decreased to a constant value below to represent the convective tower. Convective precipitation is excluded from the water path, meaning that the radiation scheme does not "see" the convective rain and snow.

The effective radius of cloud droplets is modelled as a function of cloud water content and droplet number concentration (Martin *et al.*, 1994), the latter being dependent on sulphate aerosol concentrations. Sulphate aerosols affect the radiation budget of the model via scattering and absorption of incoming solar radiation (the direct effect**) and changes to the albedo of clouds (the first indirect effect**). The direct effect is calculated separately for the Aitken and accumulation mode of sulphate aerosol using Mie theory. The first indirect (or "Twomey") effect arises from the action of sulphate aerosols as cloud condensation nuclei (CCN): increasing the number of CCN increases the number of cloud droplets (N_d), reduces their mean effective radius and thus increases cloud albedo, since clouds with smaller droplets reflect more solar radiation. The value of N_d is determined from the number concentration of aerosol particles (Jones *et al.*, 1994) and is also subject to a minimum value, which is prescribed differently over land and over sea to reflect the presence of natural continental CCN (organic aerosols, dust, etc.). Note that the second indirect effect concerning the lifetime of clouds is not modelled (i.e. the calculation of precipitation does not allow for any dependence on N_d).

I.3.3 Boundary Layer, Surface Exchange and the Land-Surface

The boundary layer can occupy up to the bottom five model layers. A first order turbulent mixing scheme is used to vertically mix the conserved thermodynamic variables and momentum (Smith, 1990). Over land, surface characteristics (such as vegetation and soil types) are prescribed according to climatological surface type, but at sea points the roughness length over open water is computed from local wind speeds (Charnock, 1955) with a lower limit of 10^{-4}m in calm conditions. Partial sea ice cover is allowed in surface flux calculations at ocean points.

The land surface scheme is employed is MOSES (Met Office Surface Exchange Scheme, Cox *et al.*, 1999). The soil model represents soil hydrology and thermodynamics using a 4-layer scheme for both temperature and moisture. It includes the effects of soil water phase change and the influence of water and ice on the thermal and hydraulic properties of the soil. The soil layers have thicknesses, from the top, of 0.1, 0.25, 0.65 and 2.0 metres. This choice of soil layer thicknesses is designed to resolve both the diurnal and seasonal cycles with minimal distortion. Surface runoff and soil drainage are accounted for and surface temperature is diagnosed as a skin temperature rather than being the mean temperature of top soil layer. A zero heat flux condition is imposed at the base of the soil model to conserve heat within the system. The formulation of evaporation includes the dependence of stomatal resistance to temperature, vapour pressure and CO_2 concentration. The interception of falling water by the vegetative canopy is modelled by allowing the canopy to both retain water (and thereby reducing the supply to the soil moisture store) and evaporate it back to the atmosphere. The properties of the canopy water store are spatially varying, depending upon the climatological vegetation type and fractional cover within a grid box. There is assumed to be only one vegetation type and one soil type per grid box. The surface albedo is a function of snow depth, vegetation type and also of the temperature over snow and ice. A modification to the standard MOSES scheme is the inclusion of a radiative (as opposed to a conductive) heat coupling of vegetated surfaces to the underlying soil**.

I.3.4 Gravity Wave Drag

Gravity wave drag is applied to momentum components in the free atmosphere using a parameterization based on a prescribed sub-grid scale orographic variance field and the vertical stability profile as a function of height through the atmospheric column (Palmer *et al.*, 1986). The basic elements of the scheme are the determination of a surface stress and the distribution of this stress through the atmospheric column. The hydrostatic surface stress is dependent, among other things, on the degree of anisotropy of the sub-grid scale orography and also on the low level Froude number (a dimensionless quantity used in momentum transfer). Additionally, the calculation of the hydrostatic surface stress disregards that air which is perceived to be blocked by the sub-grid orography, i.e. the scheme is only concerned with that air which is perceived to go over the mountains rather than around them. A further feature of the scheme is the calculation of a non-hydrostatic surface stress associated with the initiation of trapped lee waves.

ANNEX II: EXAMPLES OF HADLEY CENTRE RCM RESULTS OVER REGIONS OF THE WORLD

II.1 Application over the Indian subcontinent

The single most important factor in the annual agricultural cycle of south Asia is the rainfall brought on by the summer monsoon. At the continental scale, mean summer season rainfall is fairly constant from year to year but high spatial and temporal variability leads to localised flooding or even drought conditions. Within a given monsoon season phases of low activity occur, known as break periods, as do periods of high activity, known as active periods. The typical precipitation distributions during these regimes are in anti-phase: break periods are associated with dry conditions over most of the region apart from south-east India and Bangladesh whereas active conditions bring heavy precipitation only over central India. These phenomena create significant climatic impacts throughout the whole region.

To examine how faithfully the RCM represents the Indian summer monsoon, the previous Hadley Centre RCM was used to simulate the climate of the region for the present day. Both the RCM and its driving GCM simulate realistic mean synoptic flow conditions and the main features of the monsoon season precipitation, including the break and active precipitation anomalies over central India. However, only the RCM captures the observed precipitation anomalies over the south as shown (Figure II.1).

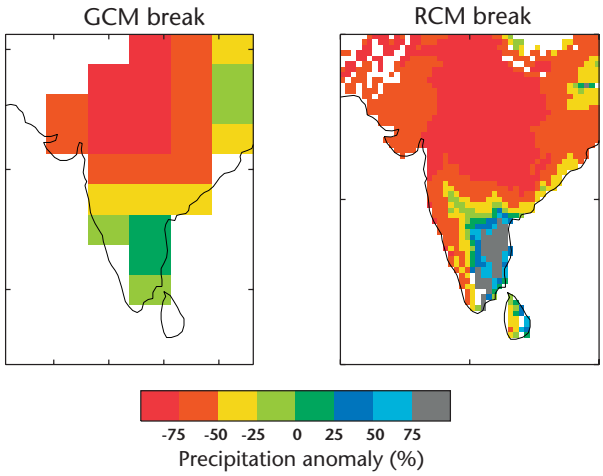


Figure II.1: *Precipitation anomaly during break periods in the GCM (left) and RCM (right) control simulations expressed as a percentage of the summer monsoon season (JJAS) mean. Sea points and areas of low daily rainfall (<1mm/day) are not shaded. (The RCM was developed in collaboration with the Indian Institute of Technology.)*

This is due to the RCM's ability to simulate extreme daily rainfall events associated with westward tracking weather systems passing over the region. The RCM is able to simulate these cyclones, preferentially in break periods as observed, and their interaction with the mountains rising steeply from the eastern coast produces the extreme rainfall. In contrast the GCM simulates weaker depressions, fewer in break periods and no enhanced rainfall over south east India. We can therefore attribute the better simulation in the RCM to an interaction between more skilfully resolved weather systems, in both structure and frequency, with the much more realistic fine-scale topography.

The RCM and the GCM were also used to project climate change by the middle of the century. The projected changes in mean monsoon rainfall in the two models are broadly similar but there are substantial regional differences. For example, over much of the Western Ghats mountain range (which runs up the west coast of India) and in parts of southern India the GCM projects a decrease in rainfall whereas the local effect seen in the RCM is actually an increase (see Figure II.2). Conversely, over a large area of central India the RCM projects decreases in monsoon precipitation, most markedly over the east coast, where the GCM indicates increases. Given that the RCM better represents the influence of the topography and the sub-seasonal variations in monsoon precipitation, we have more confidence in its projections of these regional changes.

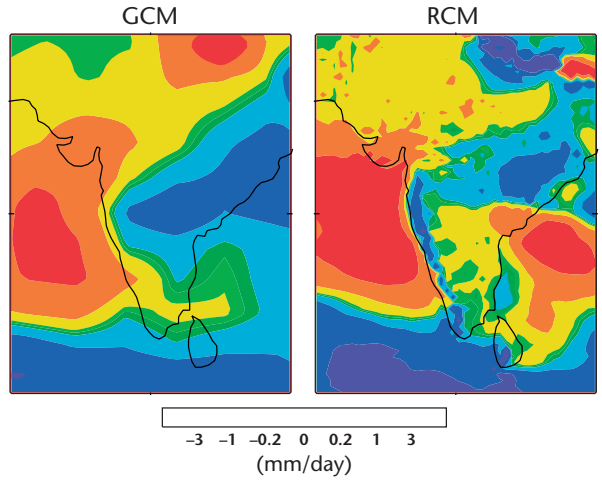


Figure II.2: *Projected changes in monsoon precipitation over India, between the present day and the middle of the 21st century from the GCM (left) and from the RCM (right).*

II.2 Application over southern Africa

Because water is a limited resource in many sub-Saharan African countries, this region may be very vulnerable to human-induced climate change. Hence, the PRECIS model has been applied to this region in order to derive high-resolution climate change projections. Under the SRES A2 emissions scenario the RCM projects an average surface warming over the subcontinent of 3.8°C in summer and 4.1°C in winter by the 2080s. It also projects a reduction in rainfall over much of the western and subtropical subcontinent, and wetter conditions over eastern equatorial and tropical southern Africa during summer when most rain falls (see Figure II.3).

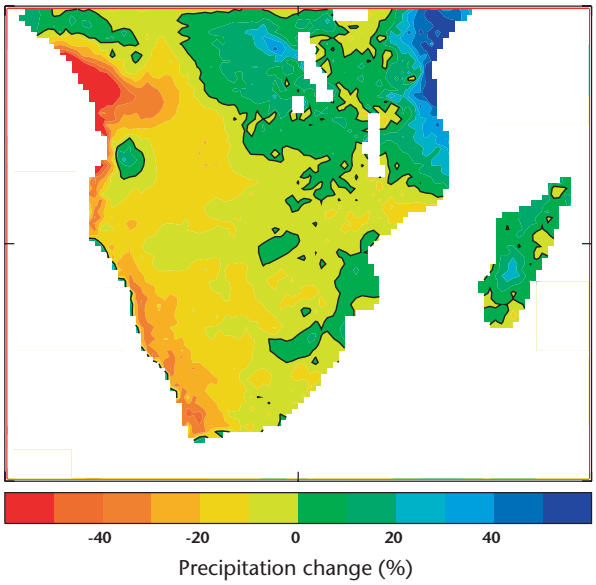


Figure II.3: *Change in mean summer (DJF) precipitation over southern Africa for the 2080s, relative to the present day, for SRES A2 emissions.*

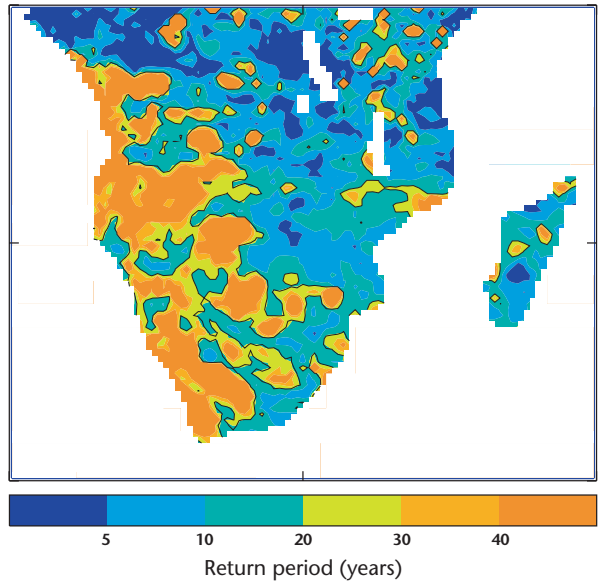


Figure II.4: *Summer rainfall return periods for the 2080s, under the A2 emissions scenario, with respect to the present-day 20-year rainfall return values. Values less than 20 imply that the present-day extreme precipitation event is more likely in the future scenario, and vice versa.*

Much of southern Africa experiences a high degree of intra- and interannual rainfall variability, and the region is particularly susceptible to floods and drought. The projected decrease in summer rainfall over the western half of the subcontinent, specifically Angola, Namibia and South Africa, is associated with a decrease in the number of rain-days, as well as a small reduction in the intensity of rainfall falling on any given rain-day. In contrast, the increase in rainfall over Tanzania and the Democratic Republic of Congo is related to an increase in the intensity of rainfall rather than a change in the number of rain-days. In the fields of hydrology and civil engineering, a common means of examining extreme rainfall is in terms of return periods. For example, structures such as bridges and dams are designed to withstand the largest precipitation event anticipated within a particular period (e.g. the one in 20-year flood event).

An analysis of the amount of rainfall associated with the one in 20-year flood event (Figure II.4) indicates that rainfall may become more extreme over large areas of Mozambique, Zimbabwe, Zambia, Tanzania and the Democratic Republic of Congo (including areas where mean precipitation is reducing), whereas less extreme rainfall is projected over western regions.

II.3 Application over Europe

The first application of the PRECIS RCM was over Europe. This has been driven by

- simulations of the current climate using observational re-analyses (ERA, from ECMWF)
- atmospheric GCM-simulated climatology from 1961-90, itself driven by the coupled atmosphere-ocean general circulation model (AOGCM) over that period
- as above, but for the period 2071-2100, under SRES A2 and B2 emissions with a three member ensemble with different initial conditions for the former (to allow an estimate of the effects of natural variability). Results from the ensemble prediction experiment are shown in Figure II.5.

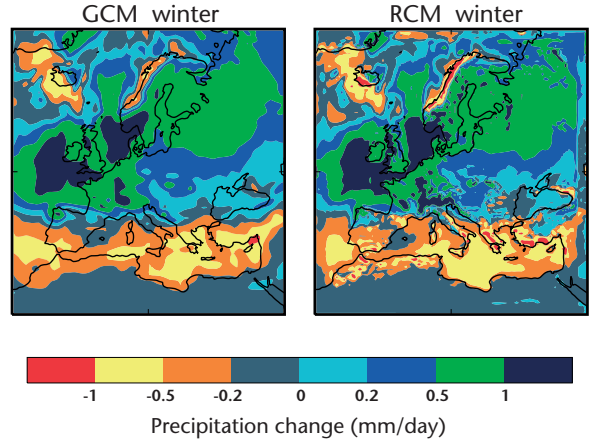


Figure II.5: *Projected changes in winter precipitation over Europe, between the present day and the end of the 21st century from the GCM (left) and from the RCM (right).*

ANNEX III: EXAMPLES OF THE USE OF PRECIS RCM-GENERATED SCENARIOS

III.1 Modelling storm surges over the Bay of Bengal

GCM data can be used for simulating coastal flooding by short-lived extreme sea-level events (i.e. storm surges) but the resolution is insufficient to provide realistic simulations. The higher resolution of the RCM allows it to drive such a model, which can project how the frequency and intensity of storm surges might change. As an example, the RCM simulation of a cyclone in the Bay of Bengal is shown in Figure III.1, together with the corresponding storm surge in the Ganges delta modelled using RCM data. As previously mentioned, GCMs do not simulate severe tropical cyclones, and hence would fail to simulate the corresponding storm surges. Of course, changes in high-water events, which could lead to coastal flooding, will also be strongly influenced by sea-level rise. This is not projected by the RCM, and therefore comes from GCM projections. While we have confidence in the global mean projections of sea-level rise, and can use them in impacts studies, we currently have much less confidence in the regional details.

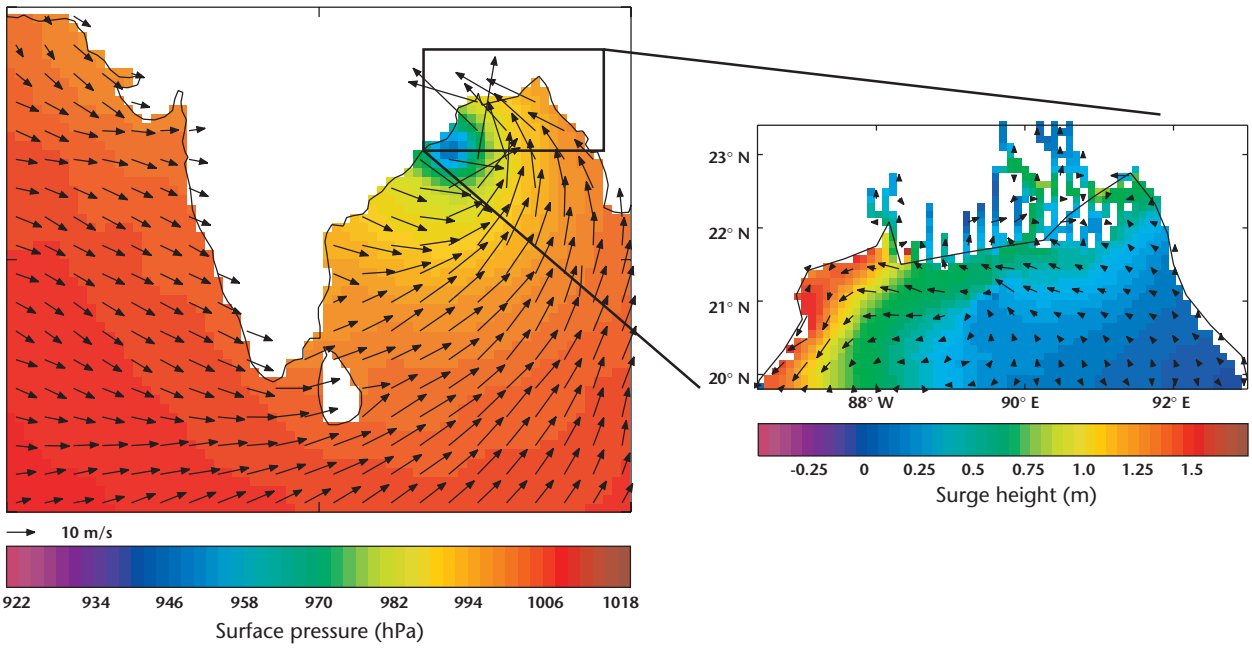


Figure III.1: *Simulated tropical cyclone and resulting storm surge. If this storm surge occurred at the time of high tide, it could cause coastal flooding.*

III.2 Climate change scenarios and their impact on water resources in southern Africa

Projections of changes in climate resulting from the A2 emissions scenario, taken from the Hadley Centre GCM and RCMs, have been applied by the University of Southampton to a hydrological model of southern Africa (Arnell *et al.*, 2003). This operates on a spatial resolution of half a degree, containing about 100 river catchments over the area shown, and uses data on precipitation, temperature, windspeed, humidity and net radiation from the climate models. The changes in monthly climate between the modelled recent climate (1961–90) and the end of the century (2071–2100) were used in various ways as input to the hydrological model. The model simulates a 30-year time series of daily surface runoff, which is summed over the whole catchment to calculate river flow, although data are only output for each month.

The study looks at different ways of constructing climate change scenarios using output from three Hadley Centre climate models. It focuses on the RCM with its spatial resolution of 0.44°x0.44° along with its driving atmospheric GCM (AGCM, resolution 1.875° x1.25°) and the coupled global ocean-atmosphere general circulation model (AOGCM, resolution 3.75°x2.5°) providing the sea-surface boundary conditions for RCM and AGCM. Sixteen climate scenarios were constructed from the three models, representing different combinations of model scale, whether climate model simulations were used directly or changes were applied to an observed baseline, and whether observed or simulated variations from year to year were used. The different ways of deriving climate scenarios from this single suite of climate model experiments resulted in a range in change in average annual runoff at a location of 10%, and often more than 20%.

There is a clear difference in the large-scale spatial pattern of change in runoff from the AOGCM and the RCM. Figure III.2 shows the change in annual average surface runoff across southern Africa, between the recent climate and that of the 2080s in the two models. The pattern of change broadly follows that in rainfall (compare right panel with Figure II.3), but with larger areas showing a reduction in river flows than in rainfall, because of the increased evaporation in the warmer future climate.

Many of the climate features in the RCM are already present in the AGCM as would be expected from the experimental design. This suggests that for studies over a large geographic domain, an intermediate-resolution GCM can produce useful scenarios for impact assessments. The RCM overestimates rainfall across much of southern Africa, so results in too much runoff: this leads to smaller estimates of future change in runoff than arise when changes in climate are applied to an observed climate baseline. It is concluded that under these circumstances it is preferable to apply modelled changes in climate to observed data to construct climate scenarios rather than derive these directly from the RCM simulations.

Incorporating simulated increases in interannual variability leads to little change in simulated annual mean runoff. However, it has a larger impact on the frequency distributions of runoff. For example, in Figure III.3, the area of substantial increase in runoff variability is much larger when changes in variability are included. This results in extreme flows being predicted to increase more than mean flows and, more importantly, peak flow increases in areas where mean flow decreases and low flow increases where mean flow increases. This demonstrates the importance of considering not only changes in mean climate but also climate variability.

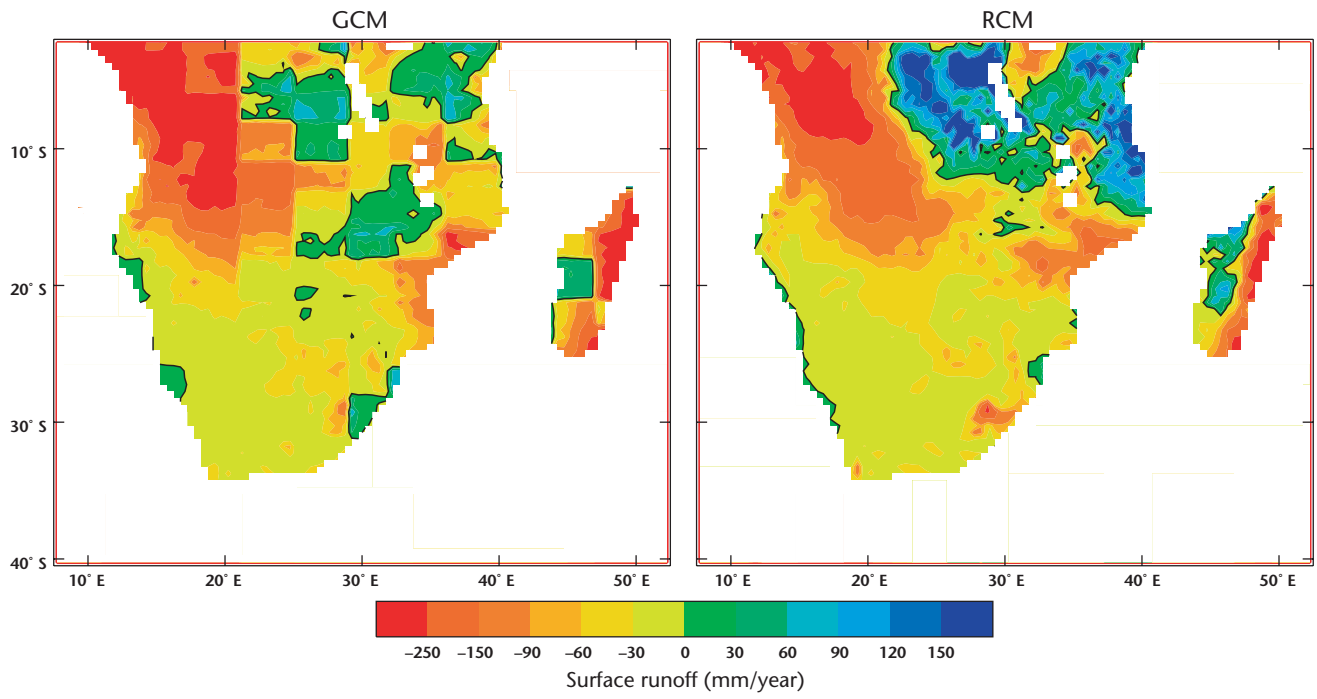


Figure III.2: *The change in annual average surface runoff between the recent climate and that projected for the 2080s as calculated from GCM projections (left) and from RCM projections (right).*

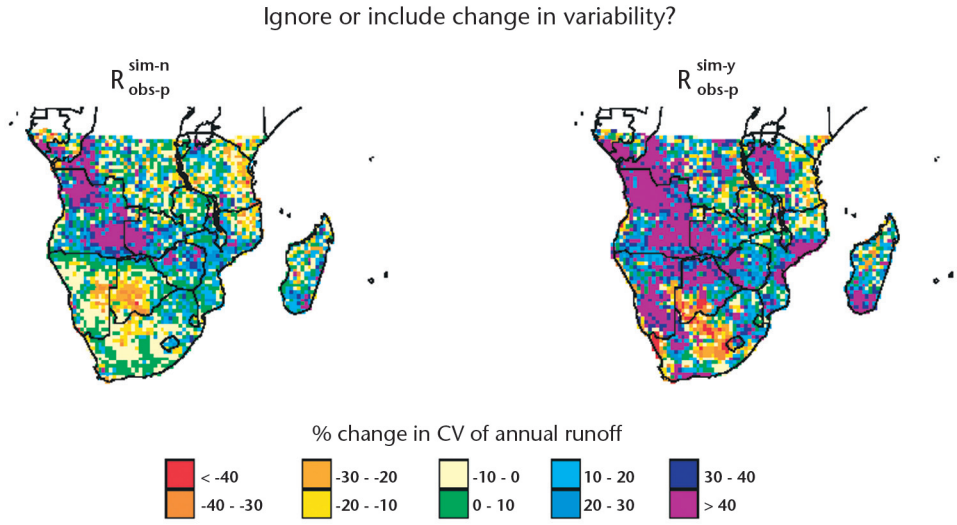


Figure III.3: *Changes in the coefficient of variation of annual runoff projected for the 2080s calculated from RCM projections either not accounting for (on the left) or accounting for (on the right) changes in precipitation variability.*

ANNEX IV: PAPERS ON HADLEY CENTRE RCMS

Refereed Publications

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PRECIS advice and technical support

Our website, http://www.precis.org.uk, is intended to provide a forum where users can exchange experiences of running PRECIS, analysing and validating its output and constructing scenarios, as well as downloading upgrades to the model. Further copies of this workbook and other documentation are available on the website, together with up-to-date information on how the PRECIS system may be obtained.

For more information or for technical support, please e-mail precis@metoffice.com.

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